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AN INVESTIGATION OF THE BOMBER AND TANKER MATING PROCESS IN THE--ETC(U)
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AN INVESTIGATION OF THE BOMBER AND
TANKER MATING PROCESS IN THE
SINGLE INTEGRATED OPERATIONS PLAN

THESIS

William L. MacElhaney, Capt, USAF
James W. Stanfield, Capt, USAF

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AN INVESTIGATION OF THE BOMBER AND TANKER MATING PROCESS IN THE SINGLE INTEGRATED OPERATIONS PLAN

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

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Graduate Strategic and Tactical Sciences

March 1982

Approved for public release; distribution unlimited

Preface

The process of assigning tankers to bombers in the Single Integrated Operations Plan is very critical. Tanker shortages require that these resources be utilized in the best way possible. The goal of this thesis effort was to find a way of improving on the current methods used in assigning tankers, and hopefully we have done so.

This goal could not have been attained without the help of many people, and we wish to thank all of those that helped us in any way.

In particular, we thank Capt Jeff Goodlett, HQ SAC/XOXF, for his enthusiastic help in providing us with all of the required data and planning documents used in our research of the problem. We thank Dr. Ken Kast of the Logicon Corporation for providing us with the methodology employed in the current Mating and Ranging Program, as well as for giving us his thoughts on our approach to the problem. We thank our thesis advisor, Major Gerald R. Armstrong, and our reader, Major Ivy D. Cook, for their helpful suggestions and conscientious guidance throughout the preparation of this thesis.

Finally, and most of all, we wish to thank our families for providing us with the encouragement and support needed to complete a long and exhausting effort. Special thanks goes to Barbara Stanfield for her many hours spent in the typing of rough drafts.

Contents

List of Abbreviations

ARCP	- Air Refueling Control Point
EAR	- End Air Refueling
EP	- Entry Point
EWO	- Emergency War Order
FF	- Fuel Flow
GW	- Gross Weight
ICBM	- Intercontinental Ballistic Missile
MARP	- Mating and Ranging Program
MRC	- Maximum Range Cruise
NM	- Nautical Mile
PRB	- Post Refueling Base
SIOP	- Single Integrated Operations Plan
SLBM	- Sea Launched Ballistic Missile
SPSS	- Statistical Package for the Social Sciences
TAS	- True Air Speed

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Abstract

The survivability of the strategic bomber force during Emergency War Order missions is of primary concern to the Strategic Air Command. Since the Soviet Union and its Warsaw Pact allies possess the most extensive air defense networks in the world, a penetrating bomber force must fly as low as possible for as long as possible. This tactic minimizes probability of detection and vulnerability to defensive threats. It also greatly increases the fuel required to complete the mission. This additional fuel is supplied by one or more in-flight refuelings.

The initial objective of this thesis was to develop a method for assigning tankers to the bomber force in an optimal manner. As the study progressed however, it became clear that obtaining a truly optimal solution using mathematical programming techniques cannot be guaranteed due to the nature and complexity of the problem. As a result the emphasis of the study was shifted to developing an improved method for solving the problem.

Two heuristic methods were investigated. The first method used network theory in an attempt to minimize the costs of assigning tankers to the bombers. The second method was based on the so-called "greedy" method. This

method basically made the assignments in the order of decreasing marginal cost improvements. These two methods were evaluated against each other and the current method by means of several example problems. Both methods yielded better results than the one currently in use, with the network method appearing to be the best.

AN INVESTIGATION OF THE BOMBER AND TANKER
MATING PROCESS IN THE SINGLE
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I. Introduction

Background

The military forces of the United States seek to deter aggression from other nations by maintaining forces capable of responding to threats across the spectrum of warfare. The United States' strategic nuclear forces deter war in general and nuclear war in particular, by maintaining a TRIAD of forces that include land-based intercontinental ballistic missiles (ICBM), submarine-launched ballistic missiles (SLBM), and manned bombers.

The manned bomber leg of the TRIAD consists of B-52 and FB-111 bomber aircraft which are supported by KC-135 tanker aircraft. The tanker aircraft add range, flexibility, and responsiveness to the bomber forces and allow them to fly long-range strike missions deep into enemy territory and return home or to post-strike bases in friendly territory (Ref 11:45).

The general profile of the bomber missions is to takeoff, fly at high altitude (to include air refueling) until reaching the perimeter of enemy defensive coverage, descend to low altitude to avoid defenses, and strike assigned targets. After striking all targets, the bomber exits enemy defensive coverage at low altitude and then climbs back to high altitude for the flight home or to post-strike bases in friendly territory.

In order to accomplish the entire mission as outlined above, a bomber may require one, two, or even three air refuelings prior to descending to low level. These refuelings are provided by tanker aircraft that may be co-located with the bomber or located at another base. In the latter case, the bomber and tanker rendezvous along the bomber's route of flight. After offloading fuel to the bomber, the tanker recovers at a pre-determined post-refueling base (PRB). This complete process is illustrated in Figure 1.

The bomber's air refueling requirements are determined by flying its mission in reverse. This is accomplished by starting at the post-strike base and working backwards to a point just prior to where the bomber has to descend to low altitude. This point is designated as the entry point (EP). The difference between the bomber's fuel at the EP without any air refueling and the fuel actually needed to complete the mission is then used to determine the onload and the number of tankers required to deliver it. Any onload less than this figure will require the bomber to use degraded tactics, i.e., descend to low

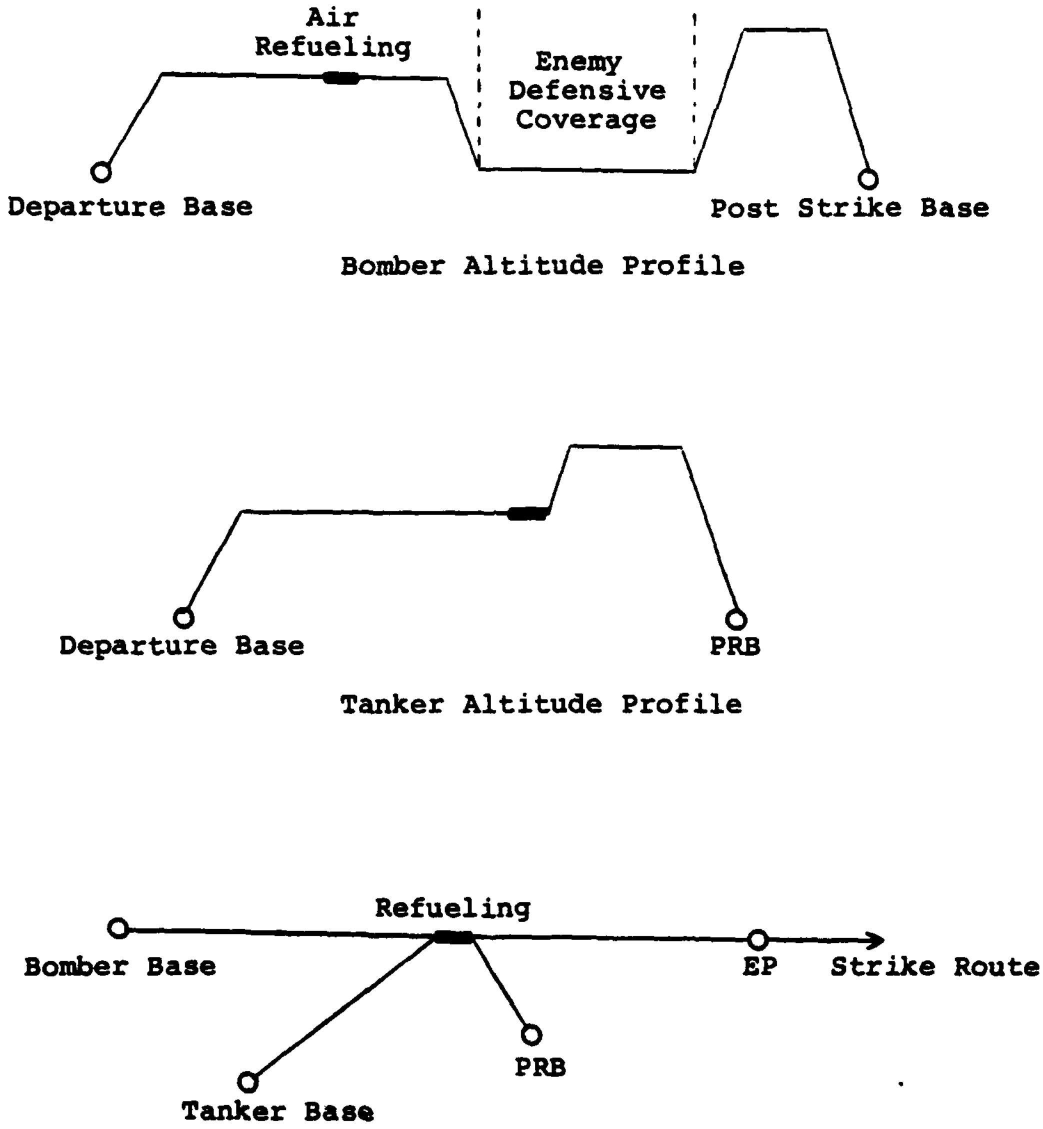


Figure 1. Bomber/Tanker Route Structure

altitude later and/or climb out of low-level earlier than desired. Unfortunately, this is the case for a large proportion of the bomber force because there are not enough tanker aircraft to provide all of the required fuel (Ref 8).

Current Procedures

Since tanker resources are limited and bomber fuel requirements are so high, it is extremely important to utilize the available tankers in the most efficient manner; however, this is easier said than done. Under full scale implementation of the Single Integrated Operations Plan (SIOP), hundreds of bombers require refuelings from an even larger number of tankers that are deployed in numerous locations, and subsequently recover at different locations. The fuel available from each of these tankers depends on where it comes from, where the refueling occurs, and where it recovers after refueling.

Prior to 1980, the mission planners at SAC Headquarters used manual procedures to accomplish bomber/tanker mating. This process involved continuous iterations until a feasible solution was obtained. It was a very arduous and time-consuming procedure, sometimes requiring several weeks to complete (Ref 8). Due to the complexity of the problem and the emphasis on a feasible solution, there was no assurance that the solution obtained was even close to optimum.

Starting in 1980, the mission planners began to use a computerized algorithm developed by the Logicon Corporation to assist them in the mating process (Ref 8). This Mating and Ranging Program (MARP) performs the entire mission-planning process including assigning tankers to bombers and determining the air refueling locations. The assignments are determined by flowing the tankers through a network, the details of which will be outlined in Chapter III. This program has aided the mission planners a great deal, but some manual calculations and matings are still required. Further efforts at improving the assignment process have met with little success to date (Ref 9).

Problem Statement

As a result of tanker shortages, a large number of bomber sorties must resort to degraded tactics in order to reach their post-strike bases with required fuel reserves. The introduction of air launched cruise missiles will further increase bomber fuel requirements. The problem then is to utilize the tanker force in the best possible manner. Ideally, the tankers should be assigned so as to meet all of the bomber EP fuel requirements. Since the tanker shortage precludes this possibility, they should then be assigned to meet as many of the requirements as possible while minimizing the shortages of those bombers whose requirements can not be met.

Objective

The objective of this research effort was to develop an optimal or near optimal methodology for mating bombers and tankers in the SIOP. The goals of this methodology are to reduce the number of bombers requiring degraded tactics and/or reduce the duration of these tactics.

Two different methods were investigated for accomplishing this objective. The first method uses a network algorithm to minimize the costs associated with assigning tankers to the bombers. This method was developed independently of the Logicon method and was believed to hold the most promise for obtaining an optimal solution. The second method is based on the "greedy" method. This method assigns tankers based on their marginal cost contributions. This method was used because it is easily implemented and has been applied to a wide variety of problems (Ref 17:59-70). It therefore served the additional purpose of being a benchmark against which both the Logicon and network methods could be evaluated.

Scope and Limitations

As previously mentioned, the full SIOP involves hundreds of bombers and tankers and numerous bases. In order to reduce the problem to manageable proportions, this study was confined to normal day-to-day alert force aircraft. Limiting the problem in this manner reduces the number of aircraft involved to under 300. Any methodology developed to handle this problem could subsequently be expanded to deal with the larger problem.

Aircraft included in the study are limited to the B-52H and the KC-135A. This limitation was imposed to take advantage of the authors' knowledge of these specific aircraft and to eliminate the complexities involved with tracking five different types of aircraft (B-52D, B-52G, B-52H, FB-111, and KC-135A) and their different performance computations. This limitation should not affect the overall solution because the basic requirements remain the same regardless of the aircraft type.

In addition to mating bombers and tankers, the Logicon program performs numerous other functions such as conflict resolutions, avoiding flight over major target complexes, and providing detailed flight plans (Ref 8). These functions were beyond the scope of this effort due to time and manpower constraints and were not considered.

Finally, most of the data involving SIOP forces is classified at the SECRET level or higher. It is for this reason that most figures are quoted as approximations only. Furthermore, the methodologies are developed and evaluated using a combination of hypothetical and real numbers and locations to avoid the problems of classification. At the same time, every effort has been made to make the various example problems as realistic as possible.

Sequence of Presentation

The remainder of this thesis is devoted to the accomplishment of the objective which was stated earlier. Chapter II details the prototype problem used to develop the methodologies and computer programs for the proposed new methods. It also outlines the assumptions used in developing and evaluating them. The theory and methodology of each of the new methods as well as the current method (MARP) are discussed in Chapter III. Each method is then used to solve the prototype problem and four additional mating problems. The results are reported and analyzed in Chapter IV. Finally, conclusions and recommendations are presented in Chapter V.

II. The Prototype Problem

Description

As noted earlier, this study was limited to the problem of mating bomber and tanker aircraft that are on normal, day-to-day alert. This limitation reduced the number of aircraft involved considerably, but it did little to diminish the complexity of the problem. Several hundred bombers and tankers from numerous locations still have to be mated for air refueling, followed by recovery of the tankers at various different locations.

Investigating a problem of this magnitude from the start would have been extremely difficult. It is for this reason that the approach to modeling advocated by William T. Morris was followed (Ref 16:707). He states:

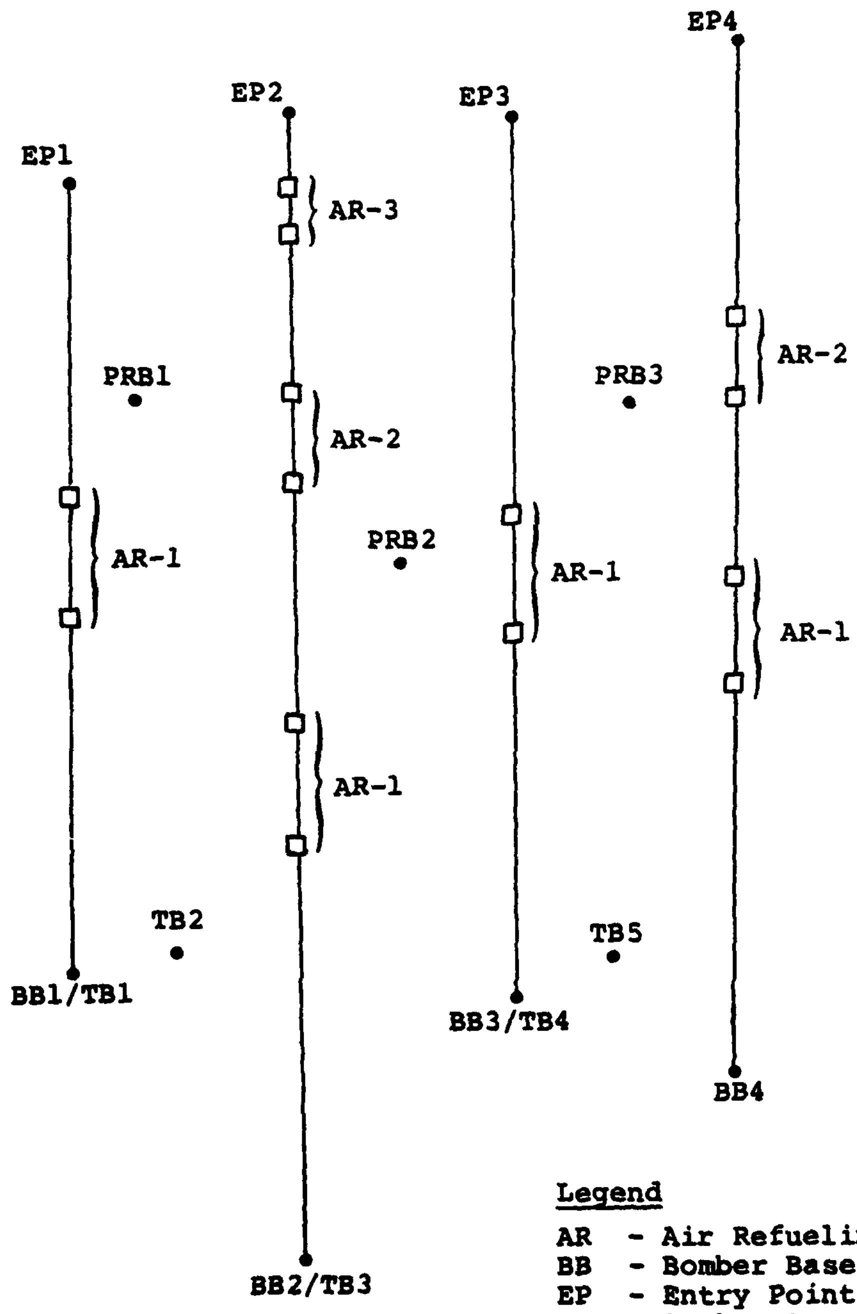
> The process of model development may be usually viewed as a process of enrichment or elaboration. One begins with very simple models, quite distinct from reality and attempts to move in evolutionary fashion toward more elaborate models which more nearly reflect the complexity of the actual management situation.

This was the process followed in the conceptualization, modeling, and computerization of this study. The initial model or prototype problem consisted of four bombers, seven tankers, and three recovery bases. In addition, the takeoff gross weights of both aircraft and their respective fuel consumption rates were assumed to be constant.

The first "enrichment and elaboration" of the prototype problem deleted all but one of the assumptions. Only the bomber's takeoff gross weight remained fixed. The tanker's takeoff gross weight and the fuel consumption rates of both aircraft were allowed to vary. This version of the problem was then further "enriched and elaborated" until the final problem consisted of 90 bombers, 135 tankers, and 18 post-refueling bases.

The prototype problem is illustrated in Figure 2. There is one bomber and tanker at each of the first three bomber bases and one bomber only at the fourth bomber base. The tanker-only bases have two tankers assigned to them. The bombers fly the routes as depicted from their bases to the entry points. Enroute they receive one or more air refuelings which are conducted on the route segments denoted by the small squares. In this particular scenario, bombers one through four receive one, three, one, and two refuelings respectively. After refueling is completed, the tankers land at the appropriate PRB. PRBs one through three have capacities of two, two, and ten tankers respectively. These capacities arise from ramp space limitations and/or servicing capabilities.

The problem then becomes how to assign the tankers to the refueling tracks and thence to the recovery bases so as to minimize the number of bombers that are short of their entry point fuel requirement and to minimize any



<u>Legend</u>

AR - Air Refueling
BB - Bomber Base
EP - Entry Point
PRB - Tanker Recovery Base
TB - Tanker Base

Figure 2. Prototype Problem

shortages. The three methods discussed in Chapter I attempt to do just this. Their success in doing so is evaluated against the prototype problem just described as well as against four additional problems. Each of the succeeding problems or models is larger than its predecessor, culminating with the one that consists of 90 bombers, 135 tankers, and 18 recovery bases.

Flight Planning

Each of the methods under investigation in this study attempt to solve the problem outlined above by maximizing the tanker offload capabilities in one manner or another. The tanker offload capabilities, in turn, are maximized by minimizing the fuel required to deliver them. The fuel requirements for delivering these offloads are in effect, the costs of this study. To minimize these costs it is first necessary to compute them. Computing these figures also requires additional computations to determine fuel consumption rates and onload and offload capabilities. The process of computing these various fuel figures is known as flight planning. This process will be discussed in detail in subsequent sections. Prior to this, however, it is necessary to review some of the underlying assumptions that apply to the mating problem and the overall flight planning process. Any additional assumptions that apply to a particular phase of the flight planning process are listed under that phase.

Assumptions

1. The number of bombers and tankers and their respective bases are fixed.

2. The available tanker recovery bases and their ramp capacities are fixed.

3. The entry point and the fuel required at that point are fixed.

4. All aircraft launch or takeoff from a ground alert posture.

5. All aircraft takeoff at the same time under an attack warning.

6. Since the bomber aircraft are not performance limited, they takeoff at their maximum allowable gross weights in accordance with standard Emergency War Order (EWO) planning factors.

7. The tanker aircraft on the other hand, are frequently performance limited because of field and climatic conditions. Therefore some aircraft takeoff at less than maximum allowable gross weight. This is also in accordance with standard EWO planning factors.

8. All aircraft fly great circle routes (most direct) from their departure bases to their entry points,

refueling tracks, and recovery bases as applicable. Avoidance of target complexes and possible route conflicts is not considered.

9. All flight planning computations are based on standard EWO planning factors or the respective aircraft performance manuals as applicable (Refs 4, 13).

10. Standard day conditions were assumed to apply throughout. The primary factor involved in this assumption is temperature. Temperatures warmer than standard generally reduce aircraft performance while colder temperatures usually enhance performance. This assumption should not affect the overall results because it applies equally to all three methods.

11. All flight planning *calculations* are based on no-wind conditions. Headwinds adversely affect range and timing considerations while tailwinds enhance them. This assumption, like standard day conditions, should not affect the final results since it also applies equally to all three methods.

12. The first possible refueling point occurs after both the bomber and tanker have leveled off and refueling must be completed prior to the entry point.

13. A bomber will never delay enroute to meet a tanker. This effectively requires a bomber's tanker to be co-located with the bomber or to be located forward of the bomber's route of flight. For example, the tanker located

at tanker base 3 of Figure 2 can not refuel any of the other bombers, because they would have to delay enroute so that the tanker could join them. On the other hand, tankers from tanker bases 1, 2, or 4 can refuel bomber 2 because they are located forward of the bomber's route of flight. The test as to whether a particular tanker can refuel a given bomber is based upon arrival time at the start refueling point which is designated as the air refueling control point (ARCP). If the tanker can arrive at the ARCP at or prior to the bomber's arrival time, the refueling is feasible. If not, the refueling is infeasible.

14. If a tanker arrives at the ARCP prior to its bomber, it will enter a holding pattern at the ARCP and await the bomber.

15. The maximum number of refuelings for a bomber is three.

Flight Planning Process

For the purposes of this study, the flight planning process has been divided into four phases. These phases are takeoff to the ARCP, holding at the ARCP, air refueling, and post-air refueling. These phases are illustrated in Figure 3 and discussed below.

Takeoff to the ARCP. Takeoff, climb, level-off, and enroute cruise to the ARCP are included in this phase of flight planning. Standard EWO planning figures were

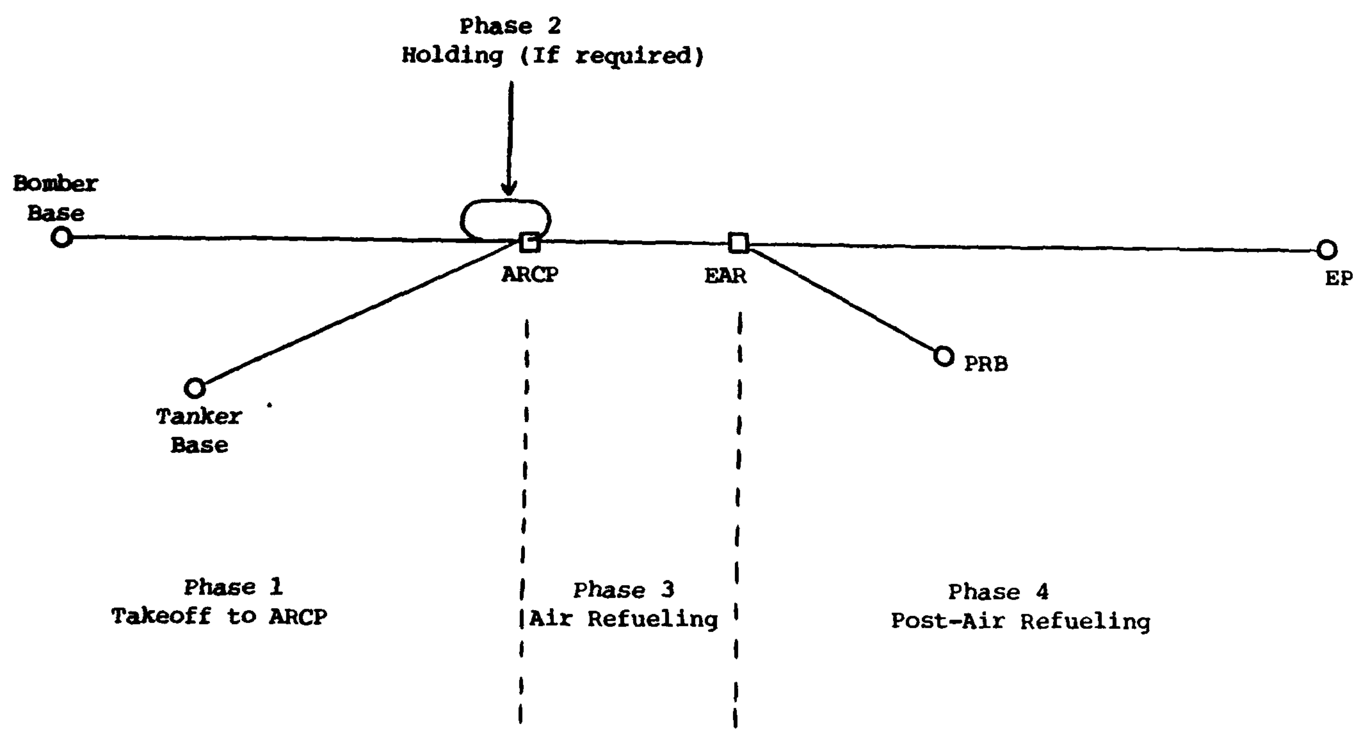


Figure 3. Flight Planning Phases

used for the time and distance from takeoff to level-off. These figures are 17 minutes and 105 NM for the bomber and 25 minutes and 164 NM for the tanker. The bomber's level-off gross weight is 476,000 pounds while the tanker's level-off gross weight varies depending on its takeoff gross weight.

After level-off both the bomber and tanker follow a maximum range cruise (MRC) profile with an average true airspeed (TAS) of 444 knots. As implied by its name, the MRC profile maximizes aircraft range by gradually climbing the aircraft as gross weight decreases due to fuel consumption. The ever increasing altitude and decreasing gross weight result in a continually decreasing fuel consumption rate. Since they are constantly changing, the fuel consumption rate and altitude are recomputed every 30 minutes in accordance with performance manual procedures. The net result of these computations is that the aircraft gross weight and arrival time at the ARCP can be computed. The gross weight can then be converted to fuel load by subtracting the aircraft zero fuel weight. These standard EWO weights are 218,300 pounds for the bomber and 110,100 pounds for the tanker. The fuels at the ARCP are important inputs for determining onload and offload capabilities.

<u>Holding at the ARCP</u>. If a tanker arrives at the ARCP before its scheduled bomber, it enters a holding

pattern to wait. Holding is accomplished at maximum endurance airspeed to minimize fuel consumption. The maximum endurance airspeed is considerably lower than cruise airspeeds and decreases as gross weight decreases. Like the cruise portion of flight, the airspeed and fuel consumption rates are recomputed every 30 minutes.

Air Refueling. Air refueling commences at the ARCP and ends at the end air refueling (EAR) point. Standard planning factors include an altitude of 30000 feet, TAS of 400 knots, and a fuel transfer rate of 5000 lbs/min from the tanker to bomber.

The bomber's capability to onload fuel is predicated on completing air refueling at its maximum inflight gross weight of 488,000 pounds. The bomber's average gross weight during air refueling is computed as follows:

$$\text{Average Gross Weight} = \frac{488000 + \text{Start Refueling Gross Weight}}{2} \quad (1)$$

The average gross weight is then used to compute the air refueling fuel consumption rate. This fuel consumption rate in lbs/min is subtracted from the 5000 lbs/min transfer rate to obtain a net transfer rate. The time required for the bomber to accomplish air refueling is then determined by the following equation.

$$\text{Time} = \frac{488000 - \text{Start Gross Weight}}{\text{Net Transfer Rate}} \quad (2)$$

Multiplying this time by the actual transfer rate of 5000 lbs/min yields the bomber's total onload capability. Its net onload capability is 488,000 minus the start refueling gross weight which also corresponds to the total onload capability minus the fuel consumed while obtaining it.

The tanker's fuel available for air refueling is determined by its start air refueling gross weight and the weight at which it has to depart for its PRB. The tanker's fuel consumption rate during refueling is also based on its average gross weight where

$$\text{Average Gross Weight} = \frac{\text{Start Gross Weight} + \text{EAR Gross Weight}}{2} \quad (3)$$

Since the tanker transfers 5000 lbs/min of fuel to the bomber, it has a net transfer rate of 5000 lbs/min plus its fuel burn rate. Dividing the fuel available for air refueling by this net transfer rate gives the tanker's time available for refueling.

$$\text{Time} = \frac{\text{Start Gross Weight} - \text{EAR Gross Weight}}{\text{Net Transfer Rate}} \quad (4)$$

Its total offload capability is the product of this time and the 5000 lbs/min transfer rate. The remainder of the fuel that was available for air refueling is consumed by the tanker itself.

Post Air Refueling. After completing air refueling, the bomber resumes its MRC profile to either the next ARCP or to the entry point, whichever is applicable. If it is the former, the computations just discussed under air refueling are repeated. If it is the latter case, the bomber's entry point fuel is determined by subtracting its zero fuel gross weight from the entry point gross weight.

After it completes refueling, the tanker resumes the MRC profile enroute to its PRB. The tanker has to terminate air refueling so as to arrive over the recovery base with its required fuel reserve. For the purposes of this study, the required fuel reserve was assumed to be 5000 pounds as the actual figure is classified.

Computing the tanker's actual EAR gross weight presents a slightly different problem in that the gross weight over the PRB is known and the EAR weight is unknown. This problem is solved by flight planning in reverse. Flight planning starts over the recovery base and proceeds backwards in 30 minute intervals to the EAR point.

Air Refueling Location

It may appear from Figure 2 and the discussion to this point that the air refueling locations are fixed, but this is not the case. As will be shown below, the optimal location of the ARCP occurs when the bomber's total onload capability equals the tanker's total offload capability. These capabilities, in turn, are functions of the bomber and tanker fuel loads at takeoff, their total time airborne, and the distance to the tanker's recovery base. If all other factors are held constant, the bomber's onload capability increases with time while the tanker's offload capability decreases. These are the natural consequences of fuel consumption over time. In a similar manner, the less fuel a bomber has at takeoff, the more fuel it can onload at any particular time. The tanker, on the other hand, has just the opposite relationship. The less fuel it has at takeoff, the smaller its offload capability at any particular instant. Finally, as the distance from end air refueling to the tanker's recovery base increases, the offload capability decreases because of the additional fuel required to reach the recovery base.

Bomber onload capability and tanker offload capability are shown as functions of time in Figure 4. For this particular combination of fuel loads and recovery base, offload capability equals onload capability at time T*. Refueling prior to this time will result in the tanker landing at the recovery base with excess fuel. Refueling after this time will result in a decreased onload for the bomber. The time T* is easily equated to distance and thus defines the optimum air refueling location along the bomber's route of flight.

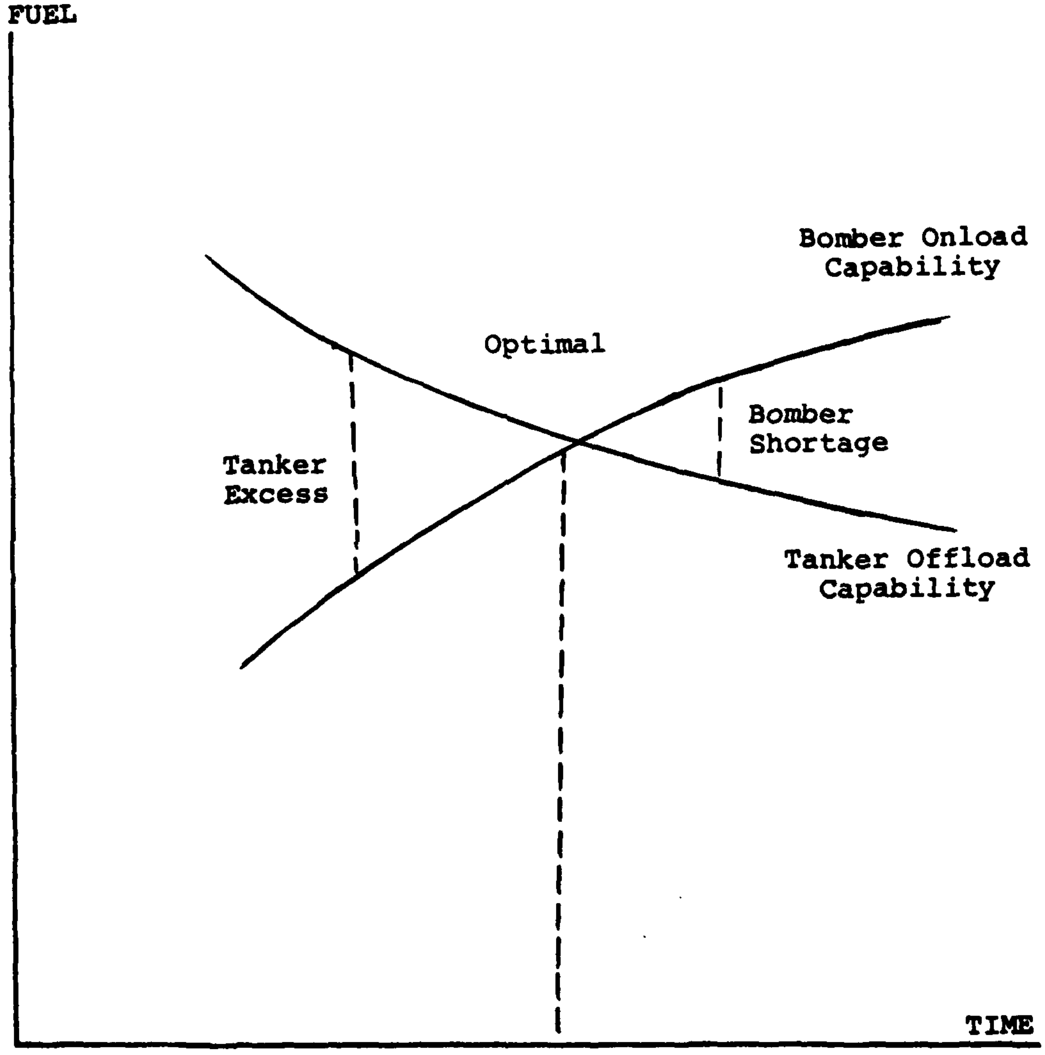


Figure 4. Fuel Onload-Offload Capabilities

Average Tanker Concept

Since all of the bombers are assumed to takeoff at the same gross weight, their onload capability is strictly a function of time. This is not the case for the tankers. Their takeoff fuel loads can vary, and this affects their offload capability. Their offload capability is also affected by distance to the PRB. As a result, it became necessary to define an average tanker for each of the three possible air refuelings. As will be seen in Chapter III, these average tankers are used to determine the number of tankers required by each bomber and to establish initial solutions for the mating problem.

The average tankers were defined by first computing the bomber's onload capability in 30-minute increments starting at 30 minutes after level-off. The tanker's offload capability was computed over the same increments based on a maximum takeoff fuel load and PRBs that were one, two, and three hours from the EAR point. These times to the PRB were selected as representative since the actual time might vary anywhere from just a few minutes to three hours or more. The resulting onload and offload capabilities are plotted graphically in Figure 5. The optimum refueling points range from approximately 3 hours and 55 minutes to 4 hours and 20 minutes after takeoff depending on the PRB. As is to be expected, a tanker with one hour PRB has the highest offload capability and a tanker with the three

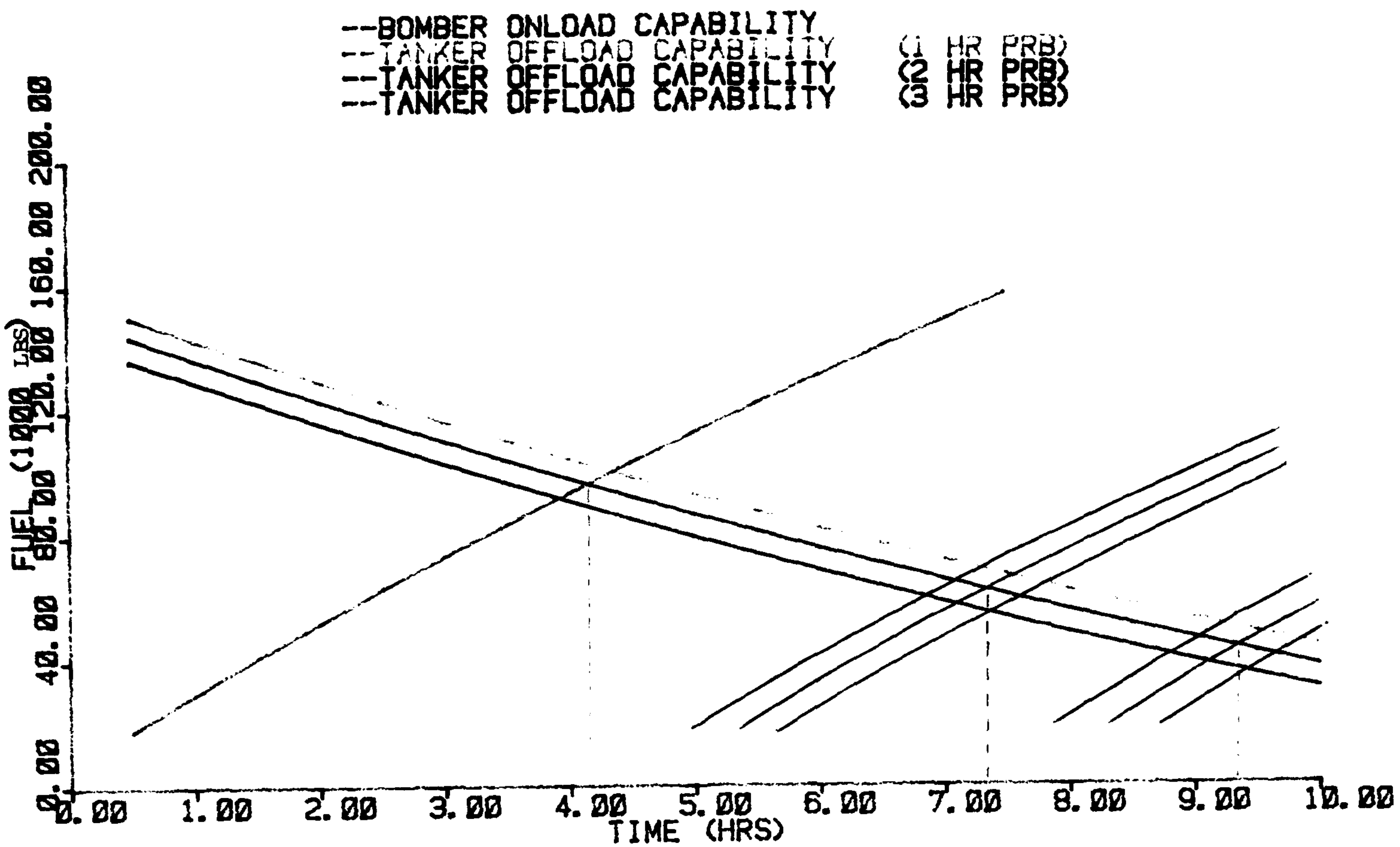


Figure 5. Onload and Offload Capabilities for Multiple Air Refuelings

hour PRB has the lowest offload capability. A complete listing of the parameters for the first refueling is shown in Table I.

TABLE I

FIRST REFUELING PARAMETERS

Time to PRB	Time from Takeoff to ARCP	Distance from Takeoff to ARCP	Onload/Off-load (1000s of lbs)	Time on Track	Track Length
1 hr	4.33 hrs	1887 NM	100.5	20.1 min	134 NM
2 hr	4.13 hrs	1800 NM	96.0	19.0 min	130 NM
3 hr	3.90 hrs	1697 NM	92.0	18.4 min	123 NM

A bomber's onload capability at any given point for the second refueling depends on its first refueling. If its first refueling was with a tanker that had a distant PRB, its onload capability will be more than if it refueled with a tanker that had a close-in PRB. This is reflected by three onload curves for the second refueling of Figure 5. These onload curves correspond to the three possibilities for the first refueling. They are identical to the original onload curve except they have been shifted to the right by the amount it took to complete the first refueling, and by the time it takes the bomber to reduce its gross weight to the same weight it had 30 minutes after initial level-off. These three onload curves then combine with the three possible tankers to produce nine onload curves for the third air refueling; however, only the onload curves corresponding to the one, two, and three hour PRBs of the second refueling are shown. Once again these curves reflect the original curve shifted by the appropriate times.

Out of all of these possible air refueling combinations, the tanker with the two hour recovery base was selected as the average. These combinations and the optimum refueling times are denoted by the dashed lines of Figure 5. The characteristics of these average tankers are listed in Table II.

TABLE II

AVERAGE TANKER CHARACTERISTICS

Refueling #	Time from Takeoff to ARCP	Distance from Takeoff to ARCP	Onload/Offload (1000s of lbs)	Time on Track	Track Length
1	4.13 hrs	1880 NM	96.0	19.0 min	130 NM
2	7.23 hrs	3160 NM	63.0	12.8 min	85 NM
3	9.27 hrs	4060 NM	44.0	9.0 min	60 NM

Variations in the tanker offload capabilities required the development of the average tanker. The average tanker, in turn, requires procedures for dealing with deviations from the average. The result of these deviations is that the offload capability will no longer equal the onload capability. This can be compensated for by shifting the ARCP. If the offload capability is greater than the onload capability, the distance to the ARCP has to be increased. Such a shift decreases the offload capability and increases the onload capability because more fuel is required to reach the ARCP. When the offload capability is less than the onload capability, the distance to the ARCP has to be decreased. This shift increases the offload capability and decreases the onload capability because less fuel is consumed to reach the ARCP. If the bomber has more than one refueling, shifting the first ARCP will require a shift in the second ARCP which will then require a shift in the third ARCP, if applicable. Shifting each of these ARCPs the appropriate distances will equalize offload and onload capabilities.

There is one final and important point that arises from the average tanker concept. Mating one bomber with one tanker that could go to three PRBs generated three refueling combinations for the first refueling, nine for the second, and twenty-seven for the third. Since the time for any tanker to reach any PRB will rarely (if ever) be identical, the end result is that the total number of refueling combinations for any given refueling is the product of the number of tankers and PRBs available. For example, assume that there are ten tankers and recovery bases available. This would result in up to 100 possible refueling combinations for a bomber on the first refueling. This would generate 100 onload curves for the second refueling, each of which can again combine with 100 possible tanker and PRB combinations. This would result in 10000 possible alternatives, each of which can again combine with 100 possible tanker and PRB combinations. Thus, ten tankers and PRBs can generate up to one million refueling combinations for only one bomber! Expanding the problem to several hundred bombers, tankers, and PRBs would generate an incredibly large number of refueling combinations. This eliminates enumeration as an effective method of optimizing the mating process.

Computerized Flight Planning

All of the flight planning to this point has been accomplished by manual look-up in the appropriate aircraft performance manuals. Such an approach is obviously not amenable to developing computerized algorithms for solving the mating problem; therefore, an attempt was made to obtain the computerized performance polynomials used by SAC and MARP. Obtaining these programs turned out to be difficult, and there was no guarantee that they could be adapted to the CDC computers if they were obtained. For these reasons, linear regression techniques were used to develop equations for the appropriate performance parameters. These parameters included:

1. B-52 maximum range cruise fuel consumption
2. B-52 fuel consumption during air refueling at 30000 feet

3. KC-135 maximum range cruise fuel consumption

4. KC-135 fuel consumption during maximum endurance holding at 30000 feet

5. KC-135 fuel consumption during air refueling at 30000 feet

All of these parameters are functions of gross weight and altitude. For the constant altitude conditions and small gross weight ranges of parameters 2, 4, and 5, fuel consumption varies almost linearly with the gross weight. This is not the case for parameters 1 and 3. The altitude is not constant, and the gross weight varies over a wider range; however, these variations can be accounted for by dividing the gross weight range into two smaller ranges. When this is done, fuel consumption again varies almost linearly with gross weight over each of these smaller ranges.

Linear regressions were run for fuel flow in pounds/minute versus gross weight in thousands of pounds for parameters 1 through 5 using the Statistical Package for the Social Sciences (SPSS) routines. The input data, the resulting equations, and a summary of the SPSS printouts are included in Appendix A. The correlation coefficient of each of these equations exceeded .98 which indicates the high degree of linearity between gross weight and fuel flow. These high correlation coefficients combined with the fact that these equations are used for all three approaches are deemed as ample justification for using the linear regression results in lieu of the performance polynomials.

The second problem encountered in the flight planning process was computation of the great circle distances. This is accomplished by using two subroutines adapted from Reference 1. Subroutine Circle computes the great circle distance between two points when given the coordinates of the points. Subroutine Latlon yields the coordinates of a second point given the coordinates of the first point and the great circle distance and course. These two subroutines are included in Appendix C.

Summary

The prototype problem, flight planning process, and the concepts of cost and average tanker were introduced and developed in this chapter because these items are pertinent to the discussion of theory and methodology which follows in Chapter III. Their treatment at this point provides the necessary background information for this discussion.

III. Theory and Methodology

Two new methods are explored for solving the bomber and tanker mating problems. They are a network method and a "greedy" method. The first method uses network theory in an attempt to obtain an optimal or near optimal assignment of bombers, tankers, and recovery bases. The second method uses a marginal cost improvement algorithm to make these assignments. Neither method offers a guarantee of optimality; however, the second is easy to implement and similar "greedy" algorithms have been employed in a wide variety of applications with varying degrees of success. Thus, it serves as a basis of comparison for both the network method and the current Logicon method.

The remainder of this chapter is devoted to the theory and methodology behind these two methods as well as the Logicon method. The network method is discussed first. It is followed by a discussion of the Logicon method. The Logicon method is included in this discussion because it is necessary to understand how it works in order to be able to better compare it with the network method. Finally, the theory and methodology of the "greedy" method are discussed.

Network Method

The underlying concept of the network method is the network. Network models have been used to solve a variety of very complex problems that include, but are not limited to transportation of goods, design of communication and pipeline systems, assignment of men to jobs, bid evaluation, and production planning (Ref 2:1).

According to the terminology of the theory of graphs, a graph consists of a set of junction points called nodes, with certain pairs of the nodes being joined by lines called arcs (Ref 10:234). Figure 6 is an example of a graph where the circles are the nodes. They are designated as 1, 2, 3, and 4. These nodes are connected by the arcs (1,2), (1,3), (2,3), (3,2), (2,4), and (3,4). As can be seen in this example, all nodes do not have to be connected, e.g., nodes 1 and 4 are not connected.

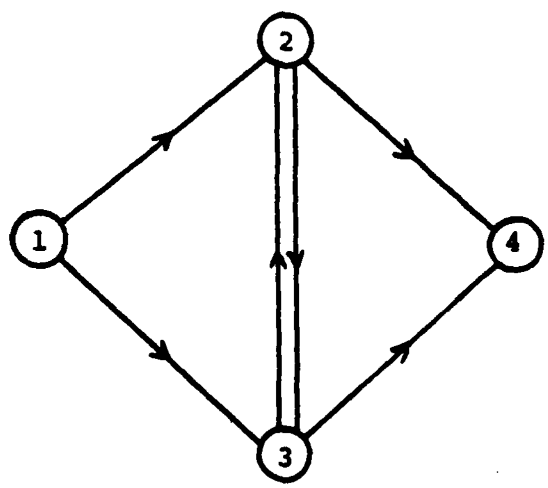


Figure 6. Example Graph/Network

A network is a graph with flow in its arcs, and is said to be directed if its arcs are oriented in a specified direction. If the arcs in Figure 6 had flow in them, this figure would be an example of a directed network with the flow indicated by the directional arrows on the arcs.

The approach of the network method is to formulate the bomber and tanker mating problem as a directed network problem. The nodes of the network are the tanker bases, ARCPs, EAR points, and PRBs. The tankers "flow" through arcs from their bases to the ARCPs, EAR points, and PRBs, respectively. The objective is to flow the tankers through this network at the minimum cost which should maximize bomber entry point fuels. As indicated in the previous chapter these costs represent the tanker fuel used in traversing the arcs.

More specifically, the network method is structured similar to the capacitated transshipment model (also known as the minimum cost flow problem) which determines in what quantities or at what rates a good should flow through the arcs of a network so as to minimize total shipment costs (Ref 6:3). The arcs of the network consist of ordered pairs of nodes (tail to head) and are indexed by k. Each arc has a shipping cost per unit of flow, C_k, a minimum allowable flow (lower bound), L_k, and a maximum allowable flow (upper bound), U_k. The nodes of the network are either supply nodes where units enter the network, demand nodes where units depart the network, or transshipment nodes where the units just pass through. The capacitated transshipment model minimizes the total costs with flows X_k that satisfy the associate upper and lower bounds and preserve the conservation of flow at each node. Mathematically, this can be expressed as

$$\text{Minimize:} \quad \sum_{k \in A} C_k X_k$$

$$\text{Subject to:} \quad \sum_{\substack{k \in A \\ \text{with tail } i}} X_k - \sum_{\substack{k \in A \\ \text{with head } i}} X_k = b_i \quad \text{for } i \in N$$

$$L_k \leq X_k \leq U_k \quad \text{for } k \in A$$

$$\text{where } b_i = \begin{cases} \text{Supply if } i \text{ is a supply node} \\ \text{-Demand if } i \text{ is a demand node} \\ 0 \text{ otherwise} \end{cases}$$

and A is the set of all arcs

N is the set of all nodes

This problem can be solved by using linear programming techniques or by using one of several special purpose network-flow computer programs. These latter programs can solve these problems up to 200 times faster than most typical linear programming codes by taking advantage of the special network structure. One such program is GNET, and it has been incorporated into the network method as a subroutine. It uses a primal-simplex method to solve the capacitated transshipment problem. This approach is considered to be much more efficient than most of the other programs which generally use an out-of-kilter approach (Ref 2:3). A full description of GNET and its capabilities is contained in Appendix D.

Initial Network Method. The methodology of the initial network method is outlined in Figure 7. It is referred to as the initial network method because it later turned out to be infeasible, and had to be altered slightly. Each of the blocks or steps of this method are discussed in turn using the prototype problem described in Chapter II for illustration purposes.

The first step consists of determining how many tankers should be assigned to each bomber. This is done by flying the bomber to its entry point unrefueled and noting how much fuel it arrives with. This figure is compared with the required entry point fuel to determine the additional fuel required. The additional fuel required is then equated to the number of tankers needed. Since the offload capability of a tanker depends on its takeoff gross weight and recovery base, the average tanker of Chapter II is used to make this determination. For convenience, the average tanker offload capabilities are repeated in Table III; however, there is one final adjustment that has to be made to these figures. As noted in Chapter II, the bomber consumes part of its onload in the process of obtaining it. In addition, the bomber is

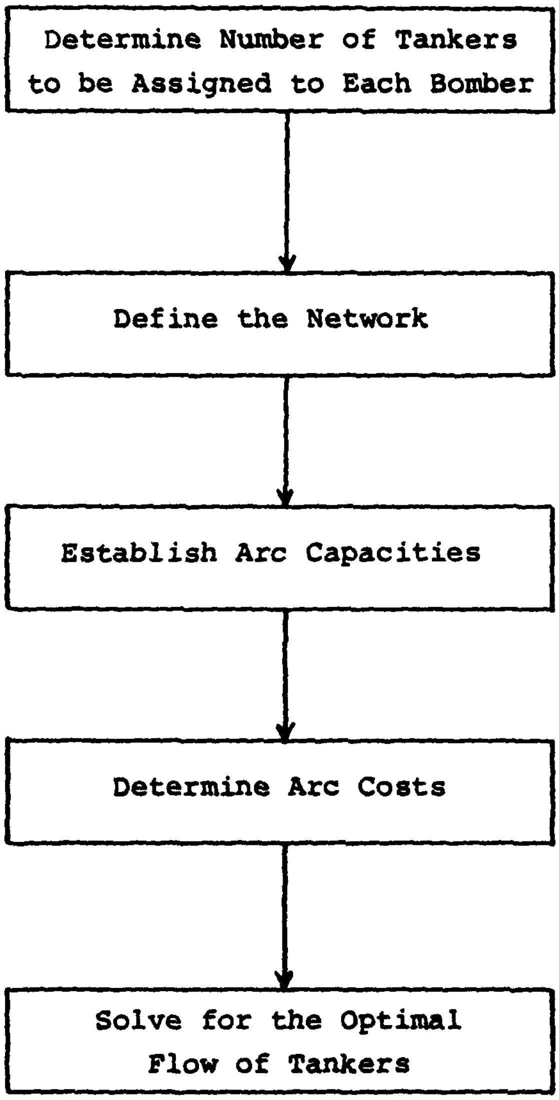


Figure 7. Initial Methodology for the Network Method

TABLE III

OFFLOAD CAPABILITIES IN THOUSANDS OF POUNDS

Refueling	Average Offload Capability	Effective Offload Capability	Cumulative Effective Offload Capability
1	96.0	83.0	83.0
2	63.0	52.0	135.0
3	44.0	29.0	164.0

heavier after refueling, and thus burns more fuel than it would if unrefueled. The net result of these two factors is that the bomber's entry point fuel with refueling is less than the sum of the tanker's offload capability and the bomber's entry point fuel without the refueling(s). This is reflected in the effective offload figures of Table III. These figures were found by computing the average net gain in entry point fuel for numerous refueling situations. The last column of Table III consists of the cumulative effective offload for one, two, and three refuelings. These are the numbers that are used to determine how many tankers are actually required to meet the bomber's entry point fuel requirement.

Table IV shows the entry point fuels without refueling, the required entry point fuels, and the additional fuel required for each of the four bombers of the prototype problem. Also shown are the tankers that would be required to supply the additional fuel requirements. If all of

TABLE IV

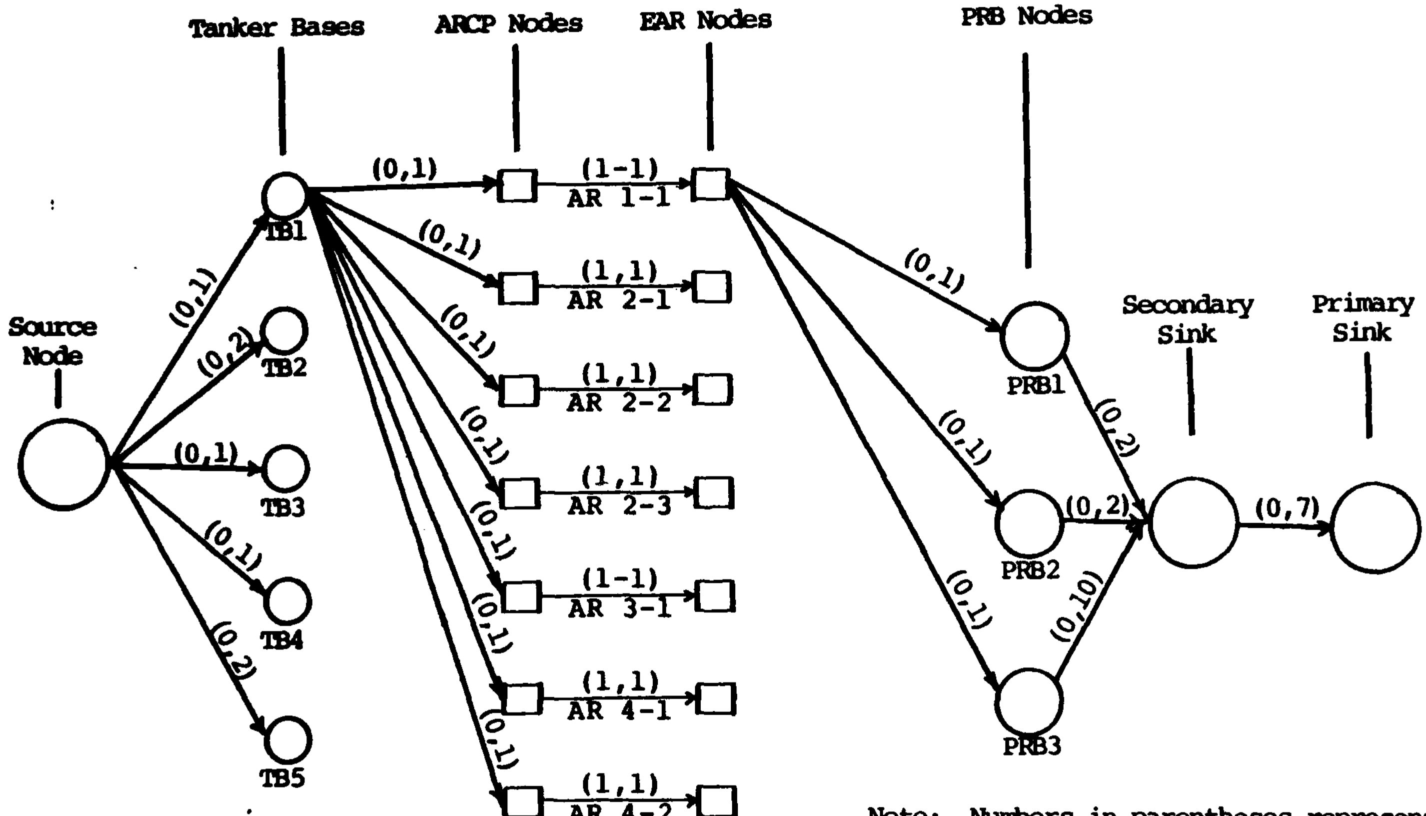
PROTOTYPE PROBLEM FUEL REQUIREMENTS IN THOUSANDS OF POUNDS

Bomber	Entry Point Fuel Unrefueled	Entry Point Fuel Required	Difference	Tankers Required	Surplus
1	123.7	205.0	81.3	1	1.7
2	90.5	250.0	159.5	3	4.5
3	118.1	220.0	101.9	2	33.1
4	98.8	250.0	151.2	3	12.8

these tankers were available, each bomber would receive fuel in excess of its requirements. The excess can be estimated by subtracting the required entry point fuel from the sum of the cumulative effective offload and the unrefueled entry point fuel. These figures are shown in the last column of Table IV.

As can be seen from Table IV, nine tankers are required to meet all of the bombers' entry point fuel requirements, but there are only seven tankers available in the prototype problem. Two refuelings have to be deleted. This is accomplished on the basis of which bomber has the greatest fuel surplus. This procedure deletes refuelings for those bombers that can best afford it. This process is continued until the tankers required equal the tankers available. For the prototype problem, bombers 3 and 4 have the largest surpluses. Each of them lose one refueling respectively.

Once the number of tankers required for each bomber has been determined, the network can be defined. The network formulation of the prototype problem is shown in Figure 8. The source node starts the flow of tankers to the tanker base nodes. These nodes are then connected to each refueling track, and from there to each post-refueling base. The post-refueling bases are in turn connected to the secondary sink node, and the secondary sink node is connected to the primary sink node. Only one sink node is required for a network problem in general, but two were required in this formulation because of Subroutine GNET. It requires two sinks because the total supply from the source node must equal the total demand at the sink node. Since the sum of all the PRB capacities exceeds the total supply of tankers that emanated from the source node, the primary sink node is required to equate the total number of tankers initially available to the number that flow into the primary sink. For the sake of clarity, only the arcs connecting tanker base 1 with each refueling track and refueling track 1 with each post-refueling base are shown. In reality, every tanker base is connected to each refueling track, and every refueling track is connected to each post-refueling base.



Note: Numbers in parentheses represent lower and upper bounds on the arc capacities. (L_k, U_k)

Figure 8. Network Formulation of the Prototype Problem

The next step of the network method involves setting the lower and upper bounds for the flows through the various arcs in the network. Each arc from the source node to a tanker base node has a lower bound of zero and an upper bound equal to the number of tankers assigned to that base. The arcs from the tanker base nodes to the ARCP nodes have a lower bound of zero and an upper bound of one. The lower and upper bounds of the air refueling arcs are both one. This insures that an air refueling takes place on each track. The arcs from the EAR points to the PRBs have a lower bound of zero and an upper bound of one. The lower bounds of the arcs from the PRB to the secondary sink are zero and the upper bounds are equal to each recovery base's capacity. Finally, the arc into the primary sink has a lower bound of zero and an upper bound equal to the total number of tankers available. As mentioned previously, this last arc insures that supply equals demand. The respective upper and lower bounds for each arc are enclosed in parentheses in Figure 8.

The fourth step of the network method computes the costs of flowing the tankers through the arcs. In this particular application, these costs represent the fuel consumed while traversing the arcs. The costs of flowing the tankers from the source to the tanker bases and from the recovery bases to the sinks are zero because these arcs are only required to establish the flow. They do not affect the total cost function. The remainder of the costs are computed using the flight planning process detailed in Chapter II. These costs include the differences in tanker takeoff gross weights, the fuel consumed from takeoff to start refueling (including holding if applicable), and the fuel consumed from the EAR point to the PRB. The first two costs are aggregated into one figure by subtracting the fuel consumed to reach the ARCP from the takeoff gross weight. This figure takes into account the fact that, although a lighter tanker consumes less fuel to reach the ARCP, it will still have less offload capability than a heavier tanker. Unlike the other costs, it is obvious that this figure should be maximized in order to maximize the offload. GNET, on the other hand, attempts to minimize costs. This discrepancy is overcome by defining this refueling cost as a negative cost. Thus, minimizing the negative cost is equivalent to maximizing the fuel available at the ARCP. One final consideration concerns infeasible bomber and tanker matings. The refueling costs for these assignments are set at a very large positive number. This prevents these tankers from being considered in the final solution. These arcs could have also been eliminated from the network, but were retained for ease of computerization.

The final step of the network method consists of solving for the optimal flow of tankers through the network.

Unfortunately, this last step proved to be impossible for this particular formulation of the problem. To obtain the optimal mating of bombers and tankers, it is necessary to assign the optimal tanker to the optimal refueling location and the optimal post-refueling base for each possible refueling; however, the optimal refueling location is a function of the tanker and recovery base assignments which are in turn functions of the refueling location. This type of problem is referred to as a three-dimensional assignment problem, and belongs to a class of problems known as NP-complete problems. There is no known polynomially bounded algorithm that is able to solve problems in this class (Ref 14:8-9). This obviously required a reformulation of the problem.

The Revised Network Method. Since there is no efficient procedure for solving the mating problem described above, an alternative or heuristic approach is required. The revised network method is such an approach. This approach utilizes the second aspect of the average tanker concept of Chapter II to eliminate one dimension of the three-dimensional assignment problem. The solution that is obtained is then iterated in an attempt to further improve the solution.

The revised network method is outlined in Figure 9. The only change in the first four steps from those of the

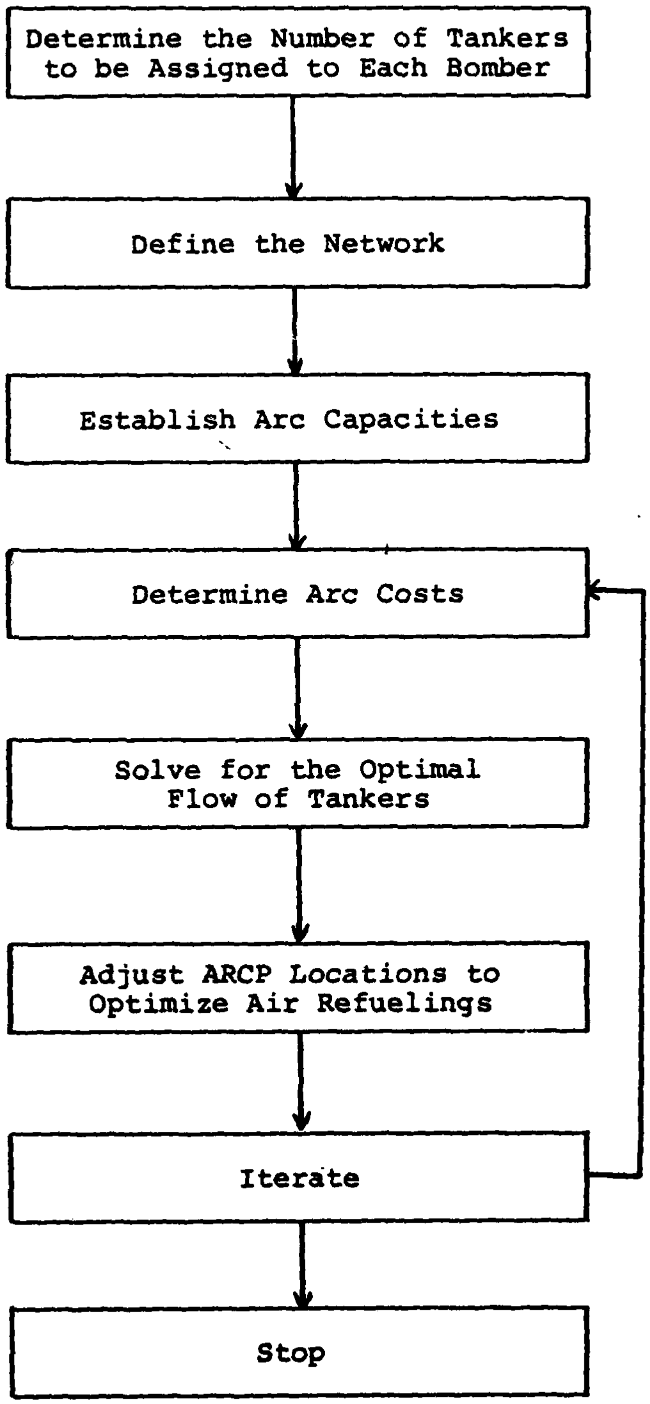


Figure 9. Revised Methodology for the Network Method

initial method is the manner in which the network is defined. The basic structure as shown in Figure 8 is unchanged; the only difference is that the ARCP and EAR point locations are no longer dependent on the tanker and PRB. They are fixed as explained in the next paragraph.

One dimension of the three-dimensional assignment problem of step 5 is eliminated by assuming that average tankers are assigned to each air refueling. This assumption fixes the locations of the refueling tracks. The distances from the bomber's departure base to the ARCPs were calculated for average tankers in Chapter II. These distances, the corresponding track lengths, and end air refueling distances are repeated in Table V. Since the air refueling location is fixed and no longer dependent on the tanker and PRB assignments, the GNET subroutine is able to flow the tankers through the network. The net result is that each tanker is assigned to the refueling tracks and PRBs so as to minimize the total cost. This provides an initial solution to the mating problem.

In reality however, the actual tanker assigned to a refueling track is rarely an average tanker. This means the refueling is not optimal because the offload and onload capabilities are not equal. The sixth step of the revised network method optimizes these refuelings. It does this by adjusting the air refueling locations (as described in Chapter II) until the offload and onload capabilities are

TABLE V

REFUELING LOCATIONS FOR AVERAGE TANKERS

Refueling	Distance from Takeoff to ARCP	Track Length	Distance from Takeoff to EAR
1	1800 NM	130 NM	1930 NM
2	3160 NM	85 NM	3245 NM
3	4060 NM	60 NM	4120 NM

within 400 pounds of each other. This 400-pound tolerance is a compromise between the desired accuracy and the computer time required to achieve it. The latter becomes a factor in large problems with many multiple refuelings because adjusting the first refueling location also requires adjusting the second and third refueling locations as applicable.

These adjustments to the air refueling locations also affect the arc costs which determined the assignments to begin with. The last step of the revised network method iterates the assignment process in an attempt to improve the solution. Each successive iteration uses the refueling locations from the previous iteration as the new initial solution. The number of iterations desired is determined by the user. For the purposes of this study, this number was initially set at ten.

The revised network method was settled upon as the network approach for solving the mating problem. It will thus be referred to as the network method for the remainder of this report.

Current Method

Since the objective of this research effort is to develop an improved method for solving the bomber and tanker mating problem, it is desirable to compare any proposed methods to the one currently in use. This method is Logicon Corporation's Mating and Ranging Program (MARP). It is an extremely large and complex program that performs many other functions in addition to solving the mating problem. It is also written in an advanced-language that is incompatible with the AFIT computers. As a result, it was not possible to use MARP itself in this study. Instead, a separate program was developed that emulates the methodology used by MARP in the assignment process. This program, referred to as the pseudo-Logicon method, is then used as the basis of comparison. The methodologies of MARP and the pseudo-Logicon method which was developed for this study are discussed below.

MARP. The methodology of MARP is similar to that of the network method in that it also uses network theory to obtain an optimal or near optimal solution to the bomber and tanker mating problem. It also defines costs in a manner similar to the network method, and then flows the tankers through a network to minimize these costs. The network has a slightly different structure because a different network solving algorithm is used. This algorithm is known as PNET and also uses a primal-simplex method to solve the capacitated transshipment problem (Ref 12).

Up to this point, there are very few differences between MARP and the network method. There is, however, one major difference. This concerns their handling of the post-refueling bases. MARP assigns each tanker to the best (closest) post-refueling base without regard to the recovery base's capacity. After all assignments have been made, it then checks to see if any PRB capacities have been exceeded. If they have been, it reassigns the excess tankers to other unsaturated PRBs. These tankers are reassigned on the basis of their bombers' entry point fuel states. First, they are ranked in the order of weakest to strongest entry point fuel state where the weakest bomber is the one that is the furthest below its desired entry point fuel. Then the tanker associated with the weakest state is reassigned first. It is sent to the next best (closest) PRB relative to its EAR point. This process is continued until all tankers are reassigned. Assigning them from the weakest to the strongest insures that the tankers most able to afford it are reassigned to the farthest PRBs (Ref 15).

Since changing the PRBs affects the tankers' offload capabilities, MARP then readjusts the refueling locations so as to equalize offload and onload capabilities.

The final step of the MARP method perturbates the solution to see if it can be improved. This step consists of aribitrarily changing a limited number of tanker assignments and seeing if any improvements are made in the entry point fuels. If an improvement is attained, these new tanker assignments become the final solution. Otherwise, the original solution stands.

Pseudo-Logicon Method. This method, as developed by the authors, duplicates MARP through a three-step process. The first step uses the network method to obtain the initial bomber and tanker matings without regard to PRB capacities. This is accomplished by making each PRB capacity equal to or greater than the total number of tankers available.

The second step, like MARP, checks each PRB to see if its actual capacity has been exceeded. If so, it reassigns the excess tankers using the same logic as MARP and readjusts the refueling locations.

The final step then repeats or iterates the entire process as in the network method. That is, the refueling locations of the initial solution become the new fixed locations for the next iteration of the network method. This step, if anything, should be superior to the limited perturbations of the MARP method.

It is not claimed that the pseudo-Logicon method is identical to the MARP method, but is believed to be close enough to serve as a basis of comparison with other methods. In fact, the iterative process may be an improvement over MARP. If this is the case, it biases the comparisons in favor of MARP.

The "Greedy" Method

The "greedy" method is similar to the Vogel Approximation Method which has enjoyed widespread use as a method of finding an initial feasible solution to a transportation problem (Ref 10:134). The "greedy" method developed for this study employs a fairly simple algorithm and is best illustrated with an example. Such an example is shown in Figure 10. This example is a typical assignment problem where the objective is to assign the machines to the jobs at minimum cost.

The first step is to compute the costs, if necessary. For this example, the costs are given. The next step is to find the difference between the smallest and next smallest cost in each row. These differences are shown in the difference column of Figure 10. The first machine to be assigned is the one with the largest difference. This corresponds to machine 4 of Figure 10a. Machine 4 is then assigned to the job that results in the lowest cost. This is job 3 which is circled. Machine 4

Machine	Job				Difference
	1	2	3	4	
1	2	5	4	6	2
2	3	6	7	5	2
3	2	4	5	4	2
4	5	5	2	6	3

a.

Machine	Job			Difference
	1	2	4	
1	2	5	6	3
2	3	6	5	2
3	2	4	4	2

b.

Machine	Job		Difference
	2	4	
2	6	5	1
3	4	4	0

c.

Figure 10. Example Problem for the "Greedy" Method

and job 3 are now eliminated from further consideration, and the process is repeated for the three remaining jobs and machines as shown in Figure 10b. Machine 1 now has the largest difference, and it is assigned to job 1. They are also eliminated from further consideration as shown in Figure 10c. Machine 2 is assigned to job 4 in this sequence. This leaves machine 3 to be assigned to job 2 by default. These job assignments are optimal in that the cost is minimized at a value of 13.

As can be seen in the example problem, this method makes assignments on the basis of the greatest marginal cost improvement, i.e., it takes the "greedy" approach. In the example problem of Figure 10a, failure to assign machine 4 to job 3 as the first step could result in a subsequent cost increase of 3. Rather than take this chance, the "greedy" method makes this assignment first and continues in this manner until all assignments are made.

Although the solution was optimal for this example, this method does not guarantee an optimal solution. This occurs for two reasons. One is the fact that ties for the largest difference are broken arbitrarily. The second, and most important, concerns the elimination step. As machines and jobs are assigned, they are eliminated from further consideration. This precludes their use in any subsequent tradeoffs to achieve optimality.

The "greedy" method uses the process just described to assign tankers to refueling tracks and post-refueling bases. The complete methodology is illustrated in Figure 11 and discussed below.

The first step, like that of the network method, determines how many tankers should be assigned to each bomber. The next step computes the cost of assigning every tanker to each of the refueling locations. Like the network method, the initial refueling locations are assumed to be those of an average tanker. The cost in this case is the sum of the fuel consumed to reach the start refueling point, the fuel available at that point, and the fuel required to reach the post-refueling base. This cost is computed for every possible tanker, refueling track, and PRB combination. If a bomber and tanker mating is infeasible due to timing, the costs are set at a large positive value. After the costs have been computed, a tanker is assigned to a particular refueling track and PRB by the "greedy" method. These refueling assignments are then adjusted to optimize the refueling as in the previous methods. The final step repeats this process using the new refueling locations as a starting point and checking for improvements.

Computerization

All three methods were programmed in FORTRAN V and run on a Control Data Corporation Cyber 750 computer.

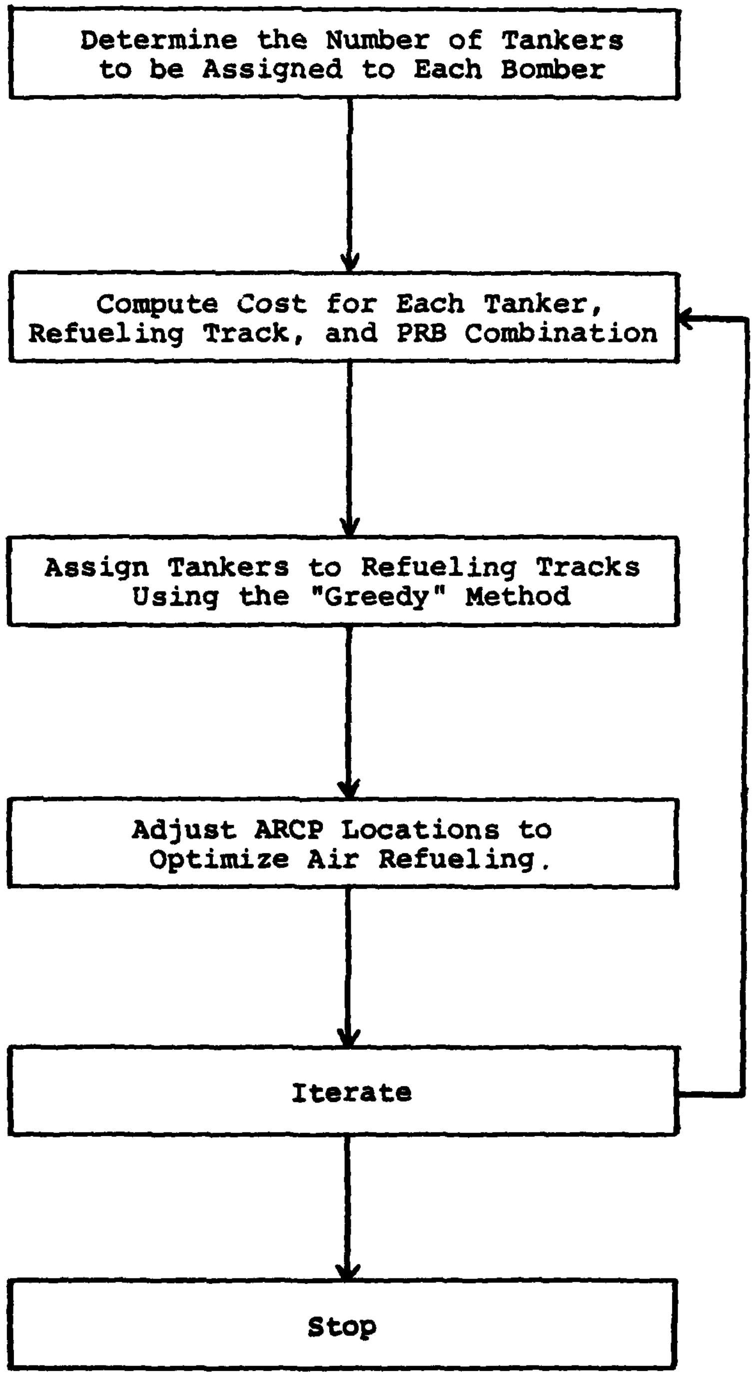


Figure 11. Methodology for the "Greedy" Method

Sample inputs and outputs from these programs are included in Chapter IV. In addition, the program listings and subroutines are included in Appendix C. Each program is documented and explained by means of comment cards which are contained in the program listings.

Verification and Validation

The validity of each program and its underlying methodology were evaluated through a three-step process adapted from the work of Fishman and Kiviat (Ref 5). The three steps of this process are:

1. Verification that the programs work as designed
2. Validation of the programs against real world problems
3. Analysis of the results

The verification and validation steps are discussed below. The analysis step is contained in Chapter IV.

Verification. Proper program operation was verified by insuring that the main functions of each program operated as designed. These functions included flight planning, determining how many tankers are required by each bomber, and the assignment process. Each of these functions are discussed in turn.

The flight planning function was checked by comparing computer derived figures against the same figures as derived from the performance manuals. This was done for all computations in the prototype problem and for selected computations from the remaining problems. In no case did the computer derived figures deviate by more than 2 percent from the performance manual figures.

The function of determining how many tankers to assign to each bomber was investigated by using numerous example problems as well as the prototype problem. There was no occasion where this function did not assign the proper number of tankers to each bomber.

The last function to be investigated was the assignment process. Although both the network and "greedy" methods are based on proven algorithms (GNET and "greedy"), they were still checked manually against example problems and the prototype problem to insure that they worked as designed. This proved to be the case.

After these functions were verified individually, the complete programs were verified against the prototype problem by manually checking the final results. The final results were also compared against each other. One final indication that each program worked as designed is that in those cases where each program assigned a tanker to the same refueling track and PRB, all geographical coordinates and fuel figures were identical. If this had not been the case, it would have indicated a fault in one or more of the programs.

Validation. The true test of validity for any problem solving method is whether or not it can solve a real world problem. This test was not applied to the methods developed for this study because of the actual problem's high degree of classification; however, these methods were used to solve example problems that were carefully formulated to resemble the actual problem. They worked as designed and expected against these problems and demonstrated face validity in that the results obtained were entirely reasonable. Thus, the methods developed for this study were validated to the extent that the sample problems captured the real world.

Summary

Three methods have been developed to solve the bomber and tanker mating problem. They are the network method, the "greedy" method, and the pseudo-Logicon method. These methods are evaluated against several problems in the next chapter.

Chapter IV. Results and Analysis

The network, "greedy," and pseudo-Logicon methods were used to solve five bomber and tanker mating problems. These problems are summarized in Table VI and listed in detail in Appendix B. The increasing sizes of these problems reflect the "enrichment and elaboration" process that was followed in the development stage of this study. All three methods were developed and proven against the prototype problem. They were then expanded to handle the larger problems on a problem-by-problem basis. This approach facilitated the programming, debugging, and validation of each method. The final goal of this process was to solve a problem the size of the normal, day-to-day alert problem. This goal was realized, and the results obtained from each method are reported and analyzed in this chapter. Problem 4 served as the primary basis of comparison because it represented the alert problem; however, the results from the other problems were studied to determine if one method consistently outperformed the others.

Input Data

The input data for each of the problems consisted of the following parameters:

1. Geographical coordinates of the bomber, tanker, and PRBs

2. The number of bombers and tankers at each base

3. The tanker level-off gross weights for each base

4. The number of PRBs and their capacities

5. Bomber entry point fuel requirements

Some of this data is included in Table VI. The complete listing for each problem is contained in Appendix B.

TABLE VI

PROBLEM SUMMARY

Problem	Bomber Bases	Number of Bombers	Tanker Bases	Number of Tankers	PRB Bases
Prototype	4	4	5	7	3
1	7	10	10	17	5
2	12	26	17	39	14
3	12	52	21	78	14
4	13	90	32	135	18

Although numbers and locations may vary somewhat from the actual figures to avoid classification difficulties, all problems other than the prototype problem have been structured to reflect the real world. This was accomplished through the following techniques:

1. Bomber and tanker bases were dispersed throughout the United States in general geographic areas that correspond to actual bases.

2. Tanker basing reflects active duty, National Guard, and Reserve alert force commitments.

3. Tanker gross weights vary according to performance limitations.

4. Bomber to tanker ratios correspond to actual figures (Ref 5:72).

5. Post-refueling bases are located in likely areas such as Alaska, Canada, Greenland, and Iceland.

Output Data

The output from each method consists of two parts. The first part displays each bomber's entry point fuel, the deviation from required entry point fuel, and the total entry point fuel for all bombers. The second part of the output lists the bomber and tanker matings, PRB assignments, air refueling coordinates, onload and offload capabilities, and time on the refueling track. Sample outputs from the network method solution to the prototype problem are displayed in Figures 12 and 13. Note that the onload and offload capabilities in Figure 13 are within the 400-pound tolerance established in Chapter III.

In addition, output from Subroutine GNET is available if desired. This output data includes the actual arc flows and costs. These outputs are not recommended for larger problems because they quickly become voluminous.

Bomber	EP Fuel Required (x1000)	Deviation (x1000)	Actual EP Fuel (x1000)
1	205.0	+ 6.20	211.20
2	250.0	+ 5.27	255.27
3	220.0	-14.98	205.02
4	250.0	-20.16	229.84
Total EP Fuel			901.33

Figure 12. Sample Output from Network Method and Prototype Problem, Part I

Bomber	Refueling Number	Tanker Base	PRB	Coordinates ARCP	Coordinates EAR	Time on Track	Onload (x1000)	Offload (x1000)
1	1	2	1	67.4, 118.4	69.5, 119.8	19.5 min	102.370	102.403
2	1	3	2	49.4, 102.5	51.6, 102.8	19.5 min	99.275	99.296
	2	1	1	73.3, 108.9	74.7, 109.9	12.8 min	66.374	66.537
	3	2	3	85.4, 139.0	86.1, 148.6	9.0 min	37.047	37.401
3	1	4	3	63.0, 93.1	65.2, 93.4	19.5 min	103.004	103.015
4	1	5	3	51.3, 79.1	53.5, 79.0	19.5 min	98.878	99.261
	2	5	3	75.0, 76.6	76.4, 76.2	12.8 min	55.417	65.383

NOTE 1: Coordinates as *shown* are for north and west, i.e., 67.4° North, 118.4° West.

NOTE 2: South and east coordinates are preceded by a minus (-) *sign*.

NOTE 3: Coordinates are listed to the nearest tenth of a minute, i.e., 118.4° West is 118° 24 min West.

Figure 13. Sample Output from Network Method and Prototype Problem, Part 2

Results

The results of running the network, "greedy," and pseudo-Logicon methods against each of the five problems are summarized in Tables VII and VIII. Table VII displays the results obtained from the first iteration for each problem. Table VIII displays the best results that were obtained, and the iteration on which they were obtained. Best in this case is defined as the maximum total entry point fuel.

The figures in these tables break down by method the number of bombers that arrive at the entry point short of the required fuel, the total fuel shortage, and the average shortage per bomber. Also shown are the number of bombers that meet or exceed the required entry point fuel, the total fuel overage, and the average overage per bomber. The final column displays the total entry point fuel for all bombers.

These figures were selected because any one of them can be used as evaluation criteria for the methods under investigation; however, the stated objective of this study was to develop a methodology to reduce the number of bombers requiring degraded tactics and/or to reduce the duration of these tactics. The evaluation criteria that correspond to this goal are the number of bombers short and the average shortage per bomber. Thus, the method that minimizes both of these criteria will obviously be the

TABLE VII

FIRST ITERATION RESULTS

Problem	Method	Bombers Short	Total Fuel Shortage	Average Shortage	Bombers Over	Total Fuel Overage	Average Overage	Total EP Fuel
	Network	2	35.14	17.57	2	11.47	5.74	901
Prototype	Greedy	2	29.11	14.56	2	7.89	3.95	904
	Logicon	2	35.14	17.57	2	7.26	3.63	897
	Network	4	37.46	9.37	6	52.40	8.73	2389
1	Greedy	4	47.48	11.87	6	54.13	9.02	2391
	Logicon	4	42.26	10.57	6	58.11	9.69	2390
	Network	15	101.47	6.76	11	77.75	7.07	6136
2	Greedy	14	124.25	8.88	12	79.85	6.65	6116
	Logicon	17	138.74	8.16	9	68.81	7.65	6090
	Network	25	203.91	8.16	27	175.30	6.49	12257
3	Greedy	31	231.88	7.48	21	165.92	7.90	12220
	Logicon	32	287.15	8.97	20	157.25	7.86	12156
	Network	42	313.08	7.45	48	343.54	7.16	21298
4	Greedy	46	351.11	7.63	44	299.02	6.80	21216
	Logicon	50	375.50	7.51	40	277.31	6.93	21211

NOTE: All fuel figures in 1000's of pounds.

TABLE VIII

BEST ITERATION RESULTS

Problem	Method	Bombers Short	Total Fuel Shortage	Average Shortage	Bombers Over	Total Fuel Overage	Average Overage	Total EP Fuel	Itera- tion
	Network	2	35.14	17.57	2	11.47	5.74	901	1
Prototype	Greedy	2	29.11	14.56	2	7.89	3.95	904	1
	Logicon	2	35.14	17.57	2	7.26	3.63	897	1
	Network	3	35.39	11.80	7	52.84	7.55	2391	3
1	Greedy	4	46.56	11.64	6	67.32	11.22	2395	4
	Logicon	3	38.15	12.72	7	43.36	6.19	2391	4
	Network	13	96.23	7.40	13	76.73	5.90	6141	5
2	Greedy	15	118.35	7.89	11	76.96	7.00	6119	2
	Logicon	17	138.74	8.16	9	68.81	7.65	6090	1
	Network	25	202.86	8.11	27	175.41	6.50	12258	2
3	Greedy	31	321.88	7.48	21	165.92	7.90	12220	1
	Logicon	32	287.15	8.97	20	157.25	7.86	12156	1
	Network	42	313.08	7.45	48	343.54	7.16	21298	1
4	Greedy	46	348.77	7.58	44	299.94	6.82	21219	4
	Logicon	50	375.50	7.51	40	277.31	6.93	21211	1

NOTE: *All fuel figures in 1000's of pounds.*

preferred method. If both criteria are not minimized by the same method, then the method that also maximizes total entry point fuel would appear to have the advantage.

A review of Tables VII and VIII shows that against the primary problem of interest, problem 4, the network method, satisfies all three criteria for the single and best iteration cases. It minimizes the number of shortages and average shortage per bomber and maximizes the total entry point fuel. As an additional check for consistency, it satisfies two of the three criteria for problems 1 through 3 on the first iteration and at least two of the three criteria for problems 2 and 3 on the best iteration. The only other method to satisfy two of the three criteria is the "greedy" method on the prototype problem and problem 1. These were the only inconsistent results noted and are most likely attributable to the small scale of the problems. These comparisons are summarized in Figure 14a.

A similar comparison of the "greedy" and pseudo-Logicon methods only in Figure 14b shows that the "greedy" method satisfies two of the three criteria for problem 4 and all of the criteria for problem 3 in both cases. For the remaining problems, "greedy" satisfies a minimum of two out of the three criteria.

Based on these comparisons, the network method appears to be the best method for solving the bomber and tanker mating problem. For problem 4 it reduces the number

Problem	First Iteration: Bombers Short	First Iteration: Average Shortage	First Iteration: Maximum EP Fuel	Best Iteration: Bombers Short	Best Iteration: Average Shortage	Best Iteration: Maximum EP Fuel
Prototype	N/G/L	G	G	N/G/L	G	G
1	N/G/L	N	G	N/L	G	G
2	G	N	N	N	N	N
3	N	G	N	N	G	N
4	N	N	N	N	N	N

a. Comparison of all Three Methods

Problem	First Iteration: Bombers Short	First Iteration: Average Shortage	First Iteration: Maximum EP Fuel	Best Iteration: Bombers Short	Best Iteration: Average Shortage	Best Iteration: Maximum EP Fuel
Prototype	G/L	G	G	G/L	G	G
1	G/L	L	G	L	G	G
2	G	L	G	G	G	G
3	G	G	G	G	G	G
4	G	L	G	G	L	G

b. Comparison of "Greedy" and Pseudo-Logicon Methods

NOTE: Method giving the best results for each criteria where

N = Network Method
G = "Greedy" Method
L = Pseudo-Logicon Method

Figure 14. Comparison of Methods

of bombers shorted by 17 percent and increased total entry point fuel by 16 percent over the corresponding figures for the pseudo-Logicon method. The "greedy" method appears to be the next best method although not by the same margin. It reduces the number of bombers shorted by 7 percent and increases total entry point fuel by 8 percent over the corresponding figures for the pseudo-Logicon method. No method showed significant advantages in reducing the average fuel shortage per bomber.

Analysis

The "greedy" and network methods appear to outperform the pseudo-Logicon method because the latter starts out with an infeasible solution, i.e., it ignores the PRB constraints. It then has to go back and send the excess tankers to unsaturated bases that may be considerable distances away. The end result is that these tankers' offload capabilities are adversely affected which in turn adversely affects the bombers' entry point fuel.

The "greedy" method, unlike the pseudo-Logicon method, deals only with feasible solutions; however, as previously noted, once it makes a tanker, bomber, and PRB assignment it is unable to go back and perform the necessary tradeoffs to improve the solution.

The network method works best because it takes all of the constraints (including PRB capacities) into account, deals only with feasible solutions, and can perform the necessary tradeoffs through the primal-simplex method to improve the solution. This is reflected in the results that were obtained.

Effects of Iteration

The prototype problem was so small that iterating had no effect on any of the methods (see Tables VII and VIII). Each iteration resulted in the same bomber, tanker, and PRB assignments. Iteration of the larger problems did result in reassignment of some tankers to different bombers or PRBs. This was an expected result because of the changed air refueling locations. The result that was not expected was the small improvements, if any, in the evaluation criteria. In some cases, all three criteria were improved. The "greedy" solution for problem 4 is one such example. In other cases no improvements were noted such as the network solution for problem 4. There were also cases where the results were mixed as in the "greedy" solution for problem 2. Finally, there were some cases where all three criteria actually decreased; however, this is not shown in Table VIII since it reflects the best iteration.

Two factors appear to be responsible for these inconsistent results. One is the large variation in tanker gross weights. These variations range from 250,000 pounds to 279,500 pounds at level-off. The other factor involved is the variable distances to the PRBs. These two factors combine to produce a large number of tankers that deviate significantly from the average tankers. These variations in turn, can require large shifts in air refueling locations in order to optimize individual air refuelings. These large shifts can significantly alter the arc costs from iteration to iteration, and there is no guarantee that the minimum cost flow on a subsequent iteration will be less than the minimum cost on the current iteration. Some refueling tracks are moved away from the bomber and tanker bases, and some are moved in the opposite direction. If the refueling track is moved away from the tanker's departure base, the tanker cost to get to the ARCP is increased. In addition, the tanker's cost from the EAR point to the PRB may also increase due to this adjustment. This increases the total cost for that tanker. With the large numbers of bombers and tankers involved, the next iteration may have a higher total cost. The net result of this argument is that contrary to our initial hypothesis, minimizing the cost of refueling does not necessarily produce the best entry point solution, but does produce a good one.

Effect of Tanker Constraints

The tanker inputs for each method include the base location, number of aircraft at a base, and gross weight.

Each of these factors can effect the mating procedure to a certain extent.

Location and Number. These factors do not affect the problem significantly because all aircraft are assumed to take-off at the same time. This also means that they are airborne for the same amount of time. Thus, the only advantage gained from being closer to the ARCP is that an aircraft may be able to hold at maximum endurance airspeed while waiting for a bomber. Holding saves fuel but the difference is not significant. For example, assume that two identical tankers are assigned to ARCPs 1000 and 2000 miles from takeoff with start air refueling times corresponding to the time it takes to fly the 2000 miles. The tanker that has to fly directly to the ARCP consumes 111,500 pounds of fuel. The tanker that flies 1000 miles and holds until the first tanker reaches its ARCP will consume 110,200 pounds of fuel. Thus, the advantage gained from being 1000 miles closer to the ARCP is only 1300 pounds.

Gross Weight. As previously discussed, large variations in the tanker gross weights result in large shifts in the air refueling locations and costs. This factor was investigated by making all tanker gross weights equal. When this was done, the network method still obtained the best results followed by the "greedy" method.

Effect of PRB Constraints

The PRB locations and capacities were the critical factors in this investigation. Routes to the entry points and locations of the PRBs caused certain PRBs to be favored over others. For example, out of 18 possible PRBs in problem 4, only 6 were used when all capacity constraints were removed. One of these had 72 aircraft assigned when its capacity was only 11. This demonstrates why the network and "greedy" methods obtain better solutions than the pseudo-Logicon method. It has to move 61 aircraft to new PRBs at an obviously large penalty.

Summary

The network, "greedy," and pseudo-Logicon methods were evaluated against five mating problems in this chapter. Input and output data were described and the results were reported and analyzed. The resulting conclusions and recommendations are presented in the next chapter.

Chapter V. Conclusions and Recommendations

Summary

The purpose of this research effort was to investigate the current methodology used to mate bombers and tankers in the Single Integrated Operations Plan with an objective of improving the process if possible. Two methods were formulated to achieve this objective. One used network theory in an attempt to obtain an optimal solution. The second used a "greedy" method to provide a feasible but not necessarily optimal solution as an alternative approach. Both of these methods were then compared to the method currently in use. This comparison was based on five problems of progressively increasing difficulty, concluding with a problem that was structured to reflect an actual SIOP mating problem.

Conclusions

The size and complexity of the bomber and tanker mating problem precludes a truly optimal solution. The interdependence of bomber and tanker assignments, air refueling locations, and PRB assignments result in a problem commonly referred to as a three-dimensional assignment problem. There is no known polynomial bounded algorithm for solving such a problem.

The network method was reformulated to fix the air refueling locations, obtain an initial feasible solution, and then iterate this solution to improve it. This revised method proved to be the best of the three methods under investigation followed by the "greedy" method.

Iterating the three methods did not result in any significant improvements to the initial solutions.

As long as PRB locations and capacities are not a factor, the current method is essentially identical to the network method; however, when these constraints are a factor, the current method is penalized because it does not take them into account until after the initial assignments have been made.

Recommendations

The Strategic Air Command should investigate the possibility of incorporating PRB capacities in the network solving algorithm employed in the Mating and Ranging Program.

Recommended Areas for Follow-on Study

The network method developed in this study should be expanded to include some sort of bomber priority in being assigned a tanker. In this way, a bomber short on EP fuel would be given a higher priority for being assigned a strong tanker. Those bombers over their EP fuel requirements would be assigned a lower priority.

A program should be developed to relate a bomber's fuel state to his probability of survival through enemy territory. For example, a bomber that meets or exceeds its EP fuel requirements would be given a survival probability of 1.0, while those not meeting their requirements would have some lower probability that would depend on the bomber's route of flight and the additional enemy defenses encountered. As a result of degraded tactics, such a program could then assign tankers based on bomber fleet survivability rather than explicit fuel requirements.

A study should be undertaken to determine the effect of using KC-10s and re-engined KC-135s in the SIOP. These aircraft offer greater fuel offload capabilities than the KC-135A, and could increase bomber entry point fuel substantially.

Comments

The addition of cruise missile commitments to the B-52 fleet in the early 1980s has a three-fold effect on the tanker assignment problems. First, the addition of cruise missiles on the aircraft decreases the bomber's fuel carrying capability. Secondly, the increased drag from these missiles increases fuel consumption. Finally, as the cruise missile carrying aircraft assume a stand-off role, they will most likely recover into bases that are currently used as tanker PRBs. This means that both tankers and bombers will be competing for the PRB space. The end result of these effects is that the tanker to bomber mating problem will become even more critical.

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Appendix A

Fuel Consumption Models

The general model used in deriving the aircraft fuel flow equations is the following:

$$FF = b_0 * GW + b_1$$

where b_0 and b_1 are constants, FF is the estimated fuel flow in pounds per minute, and GW is the aircraft gross weight in thousands of pounds. It was possible to model aircraft fuel flow in this manner since it was assumed that the aircraft fly a maximum range cruise profile, and therefore their fuel flows depend only on gross weight changes. Endurance fuel flows can be modeled the same way since a constant altitude (30,000 feet) is assumed, and air refueling fuel flows are identical to cruise fuel flows at constant altitude and airspeed with the addition of a fuel flow degradation factor. The end result of all of these factors is that all fuel flows are dependent only on changes in aircraft gross weight, and simple linear regressions can be performed for each different phase of flight for each aircraft.

The maximum range cruise (MRC) fuel flows for both aircraft were divided into two gross weight categories. The B-52 used those weights above 340,000 pounds as one category, and those weights equal to or below this weight. The KC-135 used 180,000 pounds as the dividing point. The two weight categories were used to provide a better linear estimation of the fuel flows. The two specific weights selected as dividing points were chosen because they represent weights typical of mean values encountered throughout the mission profile.

Table A-1 summarizes the data used in the KC-135 regressions, and Table A-3 contains the B-52 data. All of the data points were extracted from the appropriate aircraft performance manual, and used a standard temperature deviation of 0.

The Statistical Package for the Social Sciences (SPSS) linear regression routine was used to derive all seven fuel flow equations, and the resulting equations are shown in Table A-5.

SPSS summary tables for all equations are given in Tables A-2 and A-4. Statistically, all of the regression models are highly significant, with the lowest coefficient of determination (R^2) value being .988. This indicates that almost 99 percent of the variability of fuel flow is explained by the regression model. The high overall F values obtained in all cases confirms that gross weight contributes significantly to the regression models. All residuals (the difference between actual and predicted values) were within two standard deviations of the mean response, again indicating the validity of the model.

TABLE A-1

KC-135 DATA USED FOR FUEL FLOW REGRESSIONS

ENDURANCE AT 30,000 FEET

GW (1000s of lbs)	FF (lbs/min)
260	217.8
240	200.0
220	181.3
200	163.3
180	145.9

MRC FOR GROSS WEIGHTS GREATER THAN 180,000 POUNDS

GW (1000s of lbs)	FF (lbs/min)
280	243.5
270	233.7
260	225.3
250	217.5
240	207.9
230	198.6
220	191.0
210	182.8
200	174.3
190	165.9
180	157.2

TABLE A-1--Continued

MRC FOR GROSS WEIGHTS LESS THAN OR EQUAL TO 180,000 POUNDS

GW (1000s of lbs)	FF (lbs/min)
180	157.2
170	149.2
160	140.6
150	132.7
140	124.6
130	115.8
120	109.1

AIR REFUELING

GW (1000s of lbs)	FF (lbs/min)
210	180.0
200	173.4
190	165.9
180	160.9
170	154.8
160	150.5
150	145.5
140	141.6
130	138.2

TABLE A-2

SPSS SUMMARY TABLES FOR THE KC-135A

ENDURANCE AT 30,000 FEET	
Overall F	22890.1
Significance	.000
Multiple R	.999
R Square	.999

MRC FOR GROSS WEIGHTS GREATER THAN 180,000 POUNDS	
Overall F	22662.5
Significance	.000
Multiple R	.999
R Square	.999

MRC FOR GROSS WEIGHTS LESS THAN OR EQUAL TO 180,000 POUNDS	
Overall F	6911.1
Significance	.000
Multiple R	.999
R Square	.999

AIR REFUELING	
Overall F	553.6
Significance	.000
Multiple R	.993
R Square	.988

TABLE A-3

B-52H DATA USED FOR FUEL FLOW REGRESSIONS

MRC FOR GROSS WEIGHTS GREATER THAN 340,000 POUNDS

GW (1000s of lbs)	FF (lbs/min)
476	350.3
470	348.5
460	341.6
450	333.8
440	326.0
430	317.3
420	312.1
410	305.2
400	296.5
390	289.6
380	283.5
370	277.4
360	268.6
350	261.8
340	253.2

MRC FOR GROSS WEIGHTS LESS THAN OR EQUAL TO 340,000 POUNDS

GW (1000s of lbs)	FF (lbs/min)
340	253.2
330	248.8
320	242.8
310	235.8
300	229.8
290	220.0

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TABLE A-3--Continued

AIR REFUELING

GW (1000s of lbs)	FF (lbs/min)
450	445.0
440	437.0
430	426.6
420	417.2
410	411.0
400	403.7
390	395.4
380	388.1
370	380.8
360	374.5

TABLE A-4

SPSS SUMMARY TABLES FOR THE B-52H

MRC FOR GROSS WEIGHTS GREATER THAN 340,000 POUNDS

Overall F	13814.1
Significance	.000
Multiple R	.999
R Square	.999

MRC FOR GROSS WEIGHTS LESS THAN OR EQUAL TO 340,000 POUNDS

Overall F	667.3
Significance	.000
Multiple R	.997
R Square	.994

AIR REFUELING

Overall F	2263.5
Significance	.000
Multiple R	.998
R Square	.996

TABLE A-5

SUMMARY OF REGRESSION EQUATIONS

KC-135A:	
Endurance	FF=.9025*GW-16.89
MRC@ GW GT 180,000 lbs	FF=.8564*GW+ 2.83
MRC@ GW LE 180,000 lbs	FF=.8132*GW+10.80
Air Refueling	FF=.5237*GW+67.71
B-52H:	
MRC@ GW GT 340,000 lbs	FF=.7178*GW+10.27
MRC@ GW LE 340,000 lbs	FF=.6286*GW+40.73
Air Refueling	FF=.7837*GW+90.53

FF = Fuel Flow in lbs/min
GW = Aircraft Gross Weight in 1000s of lbs

Appendix B

Data Sets

This appendix contains the data sets for all of the scenarios used in this report. Data sets are listed as they were input to each of the models. Bomber input data was stored on tape 1 in the following sequence: departure latitude, departure longitude, entry point latitude, entry point longitude, and entry point fuel desired. Tanker input data was stored on tape 2 in the following sequence: departure latitude, departure longitude, gross weight at level-off, and number of tankers at this location. Recovery base input data was stored on tape 3 in this sequence: latitude, longitude, and capacity. All latitudes and longitudes were input as degrees and fractions of degrees (e.g., 35 30' was input as 35.5). Eastern longitudes and southern latitudes are input as negative numbers (e.g., 35 E is input as -35.).

PROTOTYPE PROBLEM

BOMBER DATA:

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
35.00	110.00	85.00	-150.00	205
18.00	100.00	87.00	-160.00	250
30.00	91.00	88.00	140.00	220
20.00	80.00	88.00	50.00	250

TANKER DATA:

Departure Latitude	Departure Longitude	Level-Off Gross Weight	Number
35.00	110.00	279.5	1
37.00	105.00	279.5	2
18.00	100.00	279.5	1
30.00	91.00	279.5	1
35.00	85.00	264.5	2

RECOVERY BASE DATA:

Latitude	Longitude	Capacity
65.00	115.00	2
62.00	100.00	2
65.00	85.00	10

PROBLEM ONE

BOMBER DATA:

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
38.00	121.00	78.31	-119.81	260
45.00	115.00	82.38	175.50	230
43.00	105.00	79.57	-98.72	213
43.00	105.00	80.86	-90.82	220
33.00	100.00	76.88	-88.31	255
46.00	95.00	88.78	-49.62	233
46.00	95.00	86.98	-56.22	227
32.00	94.00	77.03	-64.60	253
32.00	94.00	83.16	15.96	250
44.00	84.00	82.49	18.29	233

TANKER DATA:

Departure Latitude	Departure Longitude	Level-Off Gross Weight	Number
38.00	121.00	279.5	2
45.00	115.00	277.5	2
43.00	105.00	259.5	2
33.00	100.00	279.5	1
46.00	95.00	279.5	2
32.00	94.00	279.5	2
44.00	84.00	279.5	2
42.00	87.00	268.5	1
43.00	87.00	279.5	1
41.00	112.00	259.5	1

RECOVERY BASE DATA:

Latitude	Longitude	Capacity
69.00	50.00	5
65.00	145.00	5
75.00	55.00	5
55.00	115.00	3
52.00	107.00	3

PROBLEM TWO

BOMBER DATA:

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
38.00	121.00	78.30	-119.80	260
38.00	121.00	80.70	-133.60	220
45.00	115.00	83.60	-158.20	240
45.00	115.00	82.60	-145.40	230
43.00	105.00	79.60	-98.70	255
43.00	105.00	86.80	-142.10	222
43.00	105.00	86.90	148.80	240
47.00	100.00	88.10	144.60	235
48.00	100.00	89.20	-144.40	230
46.00	95.00	88.80	-49.60	230
46.00	95.00	85.40	-65.90	240
46.00	88.00	83.60	-70.90	218
46.00	88.00	85.50	-51.30	225
44.00	84.00	85.70	-36.80	220
44.00	84.00	83.40	-51.10	230
33.00	100.00	77.00	-84.20	255
33.00	100.00	85.80	-69.30	245
33.00	97.00	86.60	-52.90	245
33.00	97.00	77.50	-69.90	255
32.00	94.00	77.70	-77.10	250
32.00	94.00	86.20	-42.90	245
32.00	94.00	86.40	24.20	250
35.00	90.00	83.30	83.60	230
35.00	90.00	85.50	69.60	225
32.00	85.00	83.40	24.10	245
32.00	85.00	81.50	6.70	220

PROBLEM TWO--Continued

TANKER DATA:

Departure Latitude	Depature Longitude	Level-Off Gross Weight	Number
38.00	121.00	279.5	3
45.00	115.00	277.5	3
43.00	105.00	259.5	2
47.00	100.00	279.5	3
46.00	95.00	279.5	3
46.00	88.00	276.5	3
44.00	84.00	279.5	2
33.00	100.00	279.5	2
33.00	97.00	276.3	3
32.00	94.00	279.5	3
35.00	90.00	279.5	3
32.00	85.00	279.5	2
38.00	122.00	278.5	3
41.00	112.00	259.5	1
43.00	87.00	279.5	1
42.00	87.00	268.5	1
36.00	84.00	250.0	1

RECOVERY BASE DATA:

Latitude	Longitude	Capacity
62.00	150.00	5
65.00	145.00	3
55.00	115.00	3
52.00	107.00	3
75.00	55.00	3
69.00	50.00	3
65.00	155.00	1
65.00	157.00	2
49.00	54.00	3
52.00	60.00	3
64.00	68.00	3
56.00	111.00	3
54.00	110.00	3
65.00	20.00	5

PROBLEM THREE

BOMBER DATA:

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
38.00	121.00	78.30	-119.80	260
38.00	121.00	79.00	-155.10	220
38.00	121.00	80.70	-133.60	220
38.00	121.00	80.60	-122.10	250
45.00	115.00	83.60	-158.20	240
45.00	115.00	82.60	-145.40	230
45.00	115.00	83.00	-129.60	230
45.00	115.00	83.70	-134.40	224
43.00	105.00	83.30	-141.10	230
43.00	105.00	84.90	-171.10	225
43.00	105.00	85.00	141.10	220
43.00	105.00	79.60	-98.70	255
43.00	105.00	86.80	-142.10	222
43.00	105.00	86.90	148.80	240
47.00	100.00	85.90	-106.60	235
47.00	100.00	88.10	144.60	235
47.00	100.00	87.70	-108.10	230
47.00	100.00	89.20	-144.40	230
46.00	95.00	88.80	-49.60	230
46.00	95.00	85.40	-65.90	240
46.00	95.00	83.60	-63.90	240
46.00	95.00	85.50	-44.30	220
46.00	88.00	85.40	-72.90	220
46.00	88.00	83.60	-70.90	218
46.00	88.00	85.50	-51.30	225
46.00	88.00	87.00	-63.20	220
44.00	84.00	85.70	-36.80	220
44.00	84.00	84.30	-48.50	228
44.00	84.00	83.40	-51.10	230
44.00	84.00	82.90	-46.30	225
33.00	100.00	77.70	-88.80	260
33.00	100.00	77.00	-84.20	255
33.00	100.00	85.30	-69.30	245
33.00	100.00	86.70	-56.50	249
33.00	97.00	77.00	-78.80	258
33.00	97.00	86.60	-52.90	245
33.00	97.00	87.50	-24.60	256
33.00	97.00	77.50	-69.90	255
32.00	94.00	77.70	-77.10	250
32.00	94.00	86.20	-42.90	245
32.00	94.00	78.40	-69.50	251
32.00	94.00	86.40	24.20	250

BOMBER DATA--Continued

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
32.00	94.00	86.20	.20	250
32.00	94.00	85.30	-19.70	240
35.00	90.00	83.30	83.60	230
35.00	90.00	85.50	69.60	225
35.00	90.00	84.60	69.10	225
35.00	90.00	83.70	68.80	220
32.00	85.00	83.40	24.10	245
32.00	85.00	80.10	-47.90	250
32.00	85.00	82.40	-5.10	250
32.00	85.00	81.50	6.70	220

TANKER DATA:

Departure Latitude	Departure Longitude	Level-Off Gross Weight	Number
38.00	121.00	279.5	4
45.00	115.00	277.5	5
43.00	105.00	259.5	5
47.00	100.00	279.5	5
46.00	95.00	279.5	5
46.00	88.00	276.5	5
44.00	84.00	279.5	5
33.00	100.00	279.5	4
33.00	97.00	276.3	4
32.00	94.00	279.5	4
35.00	90.00	279.5	4
32.00	85.00	279.5	4
38.00	122.00	278.5	4
41.00	112.00	259.5	1
43.00	87.00	279.5	1
42.00	87.00	268.5	1
36.00	84.00	250.0	1
41.00	86.00	279.5	5
38.00	120.00	268.0	4
35.00	99.00	279.5	4
37.00	120.00	279.5	3

RECOVERY BASE DATA:

Latitude	Longitude	Capacity
62.00	150.00	8
65.00	145.00	6
55.00	115.00	8
52.00	107.00	6
75.00	55.00	8
69.00	50.00	6
65.00	155.00	1
65.00	157.00	4
49.00	54.00	6
52.00	60.00	5
64.00	68.00	6
56.00	111.00	3
54.00	110.00	6
65.00	20.00	8

PROBLEM FOUR

BOMBER DATA:

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
38.00	121.00	78.10	-125.50	250
38.00	121.00	79.30	-119.80	260
38.00	121.00	79.00	-155.10	220
38.00	121.00	80.70	-133.60	220
38.00	121.00	80.60	-122.10	250
45.00	115.00	85.00	-148.00	225
45.00	115.00	83.60	-158.20	240
45.00	115.00	82.60	-145.40	230
45.00	115.00	83.00	-129.60	230
45.00	115.00	83.70	-134.40	224
43.00	105.00	83.20	-156.70	228
43.00	105.00	83.70	-163.30	224
43.00	105.00	83.30	-141.10	230
43.00	105.00	84.90	-171.90	225
43.00	105.00	85.00	141.10	220
43.00	105.00	79.60	-98.70	255
43.00	105.00	86.80	-142.10	222
43.00	105.00	86.90	148.80	240
47.00	100.00	85.40	-70.70	235
47.00	100.00	85.90	-106.60	235
47.00	100.00	88.10	144.60	235
47.00	100.00	87.70	-108.10	230
47.00	100.00	89.20	-144.40	230
46.00	95.00	84.40	-61.10	220
46.00	95.00	88.80	-49.60	230
46.00	95.00	85.40	-65.90	240
46.00	95.00	83.60	-63.90	240
46.00	95.00	85.50	-44.30	220
46.00	88.00	84.80	-83.60	225
46.00	88.00	85.40	-72.90	220
46.00	88.00	83.60	-70.90	218
46.00	88.00	85.50	-51.30	225
46.00	88.00	87.00	-63.20	220
44.00	84.00	87.40	39.40	220
44.00	84.00	85.70	-36.80	220
44.00	84.00	84.30	-48.50	228
44.00	84.00	83.40	-51.10	230
44.00	84.00	82.90	-46.30	225
37.00	120.00	82.90	-128.80	251
37.00	120.00	84.00	-132.60	252
37.00	120.00	83.90	-115.00	250
37.00	120.00	86.00	-146.70	220
34.00	117.00	81.60	-151.20	251
34.00	117.00	81.60	173.60	220
34.00	117.00	84.20	-164.80	255

BOMBER DATA--Continued

Departure Latitude	Departure Longitude	Entry Point Latitude	Entry Point Longitude	Entry Point Fuel Desired
34.00	117.00	84.40	176.70	222
34.00	117.00	85.50	-178.50	257
33.00	100.00	75.90	-91.70	250
33.00	100.00	88.20	-123.90	256
33.00	100.00	77.70	-88.80	260
33.00	100.00	77.00	-84.20	255
33.00	100.00	85.30	-69.30	245
33.00	100.00	86.70	-56.50	249
33.00	97.00	88.70	22.30	252
33.00	97.00	86.60	-.40	250
33.00	97.00	83.90	-42.20	250
33.00	97.00	84.30	-33.50	240
33.00	97.00	77.00	-78.80	258
33.00	97.00	86.60	-52.90	245
33.00	97.00	87.50	-24.60	256
33.00	97.00	77.50	-69.90	255
32.00	94.00	78.00	-90.50	252
32.00	94.00	84.60	-76.50	251
32.00	94.00	83.70	-29.70	254
32.00	94.00	77.70	-77.10	250
32.00	94.00	86.20	-42.90	245
32.00	94.00	78.40	-69.50	251
32.00	94.00	86.40	24.20	250
32.00	94.00	86.20	.20	250
32.00	94.00	85.30	-19.70	240
35.00	90.00	86.60	103.20	219
35.00	90.00	83.30	83.60	230
35.00	90.00	85.50	69.60	225
35.00	90.00	84.60	69.10	225
35.00	90.00	83.70	68.80	220
32.00	85.00	84.90	2.20	250
32.00	85.00	83.40	24.10	245
32.00	85.00	80.10	-47.90	250
32.00	85.00	82.40	-5.10	250
32.00	85.00	81.50	6.70	220
43.00	75.00	89.20	9.90	225
43.00	75.00	85.90	-82.80	220
43.00	75.00	88.10	-29.40	230
43.00	75.00	86.30	-67.20	218
43.00	75.00	86.80	-37.90	220
46.00	68.00	87.20	-96.70	223
46.00	68.00	87.70	-73.70	227
46.00	68.00	85.20	-84.40	230
46.00	68.00	84.10	-81.30	235
46.00	68.00	85.60	-57.10	225

TANKER DATA:

Departure Latitude	Departure Longitude	Level-Off Gross Weight	Number
38.00	121.00	279.5	5
37.00	120.00	279.5	5
45.00	115.00	277.5	9
43.00	105.00	259.5	5
47.00	100.00	279.5	10
46.00	95.00	279.5	6
46.00	88.00	276.5	10
44.00	84.00	279.5	6
43.00	75.00	279.5	5
46.00	68.00	279.5	9
34.00	117.00	279.5	5
33.00	100.00	279.5	6
33.00	97.00	276.3	2
32.00	94.00	279.5	4
35.00	90.00	279.5	5
32.00	85.00	279.5	5
38.00	122.00	278.5	6
41.00	112.00	259.5	1
43.00	87.00	279.5	1
42.00	87.00	268.5	1
36.00	84.00	250.0	1
41.00	86.00	279.5	9
38.00	97.00	267.5	6
35.00	99.00	279.5	5
38.00	120.00	268.0	1
35.00	110.00	250.0	1
45.00	69.00	279.5	1
39.00	96.00	274.5	1
40.00	82.00	279.5	1
40.00	75.00	264.5	1
40.00	79.00	270.0	1
35.00	92.00	276.5	1

RECOVERY BASE DATA:

Latitude	Longitude	Capacity
62.00	150.00	11
65.00	145.00	9
65.00	157.00	5
65.00	155.00	2
55.00	115.00	11
52.00	107.00	9
54.00	110.00	9
49.00	54.00	9
64.00	68.00	10
56.00	111.00	6
52.00	60.00	8
60.00	125.00	6
75.00	55.00	11
69.00	50.00	9
65.00	20.00	11
56.00	4.00	10
60.00	95.00	6
52.00	-178.00	4

Appendix C

Computer Listings

```
      PROGRAM NETWORK
C
C     THIS PROGRAM SOLVES THE TANKER TO BOMBER TO RECOVERY BASE
C     MATING PROBLEM USING A NETWORK SOLVER THAT MINIMIZES THE
C     TOTAL TANKER FLEET FUEL CONSUMED.  ONCE TANKERS ARE
C     ASSIGNED TO BOMBERS AND PRBS, THE INDIVIDUAL REFUELING
C     LOCATIONS ARE OPTIMIZED TO MAXIMIZE BOMBER ENTRY POINT
C     FUEL.  BOMBER, TANKER, AND PRB DATA ARE INPUTS TO THE
C     PROGRAM, AND THE INDIVIDUAL ASSIGNMENTS AND REFUELING
C     LOCATIONS ARE THE OUTPUTS.  ITERATIONS CAN BE MADE IN AN
C     ATTEMPT TO IMPROVE THE ASSIGNMENT PROCESS, AND INDIVIDUAL
C     BOMBER FUELS AT THE ENTRY POINT CAN BE OUTPUT AS WELL.
C
C
      COMMON/FACTOR/PI,RAD
C
C            FILE DEVICES USED IN THIS PROGRAM:
C
C     TAPE 1 ......................BOMBER INPUT DATA
C     TAPE 2 ......................TANKER INPUT DATA
C     TAPE 3 ......................RECOVERY BASE INPUT DATA
C     TAPE 5 ......................INPUT FOR GNET SUBROUTINE
C     TAPE 6 ......................OUTPUT FROM GNET SUBROUTINE
C     TAPE 7 ......................OUTPUT FROM GNET SUBROUTINE
C     TAPE 9 ......................COST OUTPUT FROM GNET
C
C
C
C            INDEX OF IMPORTANT VARIABLES
C
C
C     NOTRKS..............NUMBER OF BOMBER TRACKS
C     NOTB................NUMBER OF TANKER BASES
C     NOPRB...............NUMBER OF POST REFUELING BASES
C     NOTAVL..............NUMBER OF TANKERS AVAILABLE
C
C
C     ARRAYS SHOULD BE DIMENSIONED AS FOLLOWS:
C
C     BBLAT,BBLON,EPLAT,EPLON,EPFREQ.........NOTRKS+1
C     TBLAT,TBLON,TKGWT,NOTKRS...............NOTB+1
C     PRBLAT,PRBLON,PRBCAP...................NOPRB+1
C     DIST,COURSE,DIFF,UNREF,FUELS,NOTREQ,
C     XDIF,EFFACT,XXDIF......................NOTRKS
C     CPLAT,CPLON,EARLAT,EARLON,FESTIM,
C     ARDIST,ENDDIS,FUELOF,BOMBON,YY,
C     FARGWT,PBLAT,PBLON.....................NOTAVL
C     COST1,ARCPGW...........................NOTB,NOTAVL
C     COST2,EARGWT...........................NOTAVL,NOPRB
C     ARDIS,EARDIS...........................3
C
C
```

```
      INTEGER NOTKRS(41),NOTREQ(91),PRBCAP(26)
      REAL BBLAT(91),BBLON(91),EPLAT(91),EPLON(91),EPFREQ(91),
     &TBLAT(41),TBLON(41),TKGWT(41),PRBLAT(26),PRBLON(26),
     &DIST(91),UNREF(91),FUELS(91),XDIF(91),ARDIS(3),
     &EARDIS(3),COURSE(91),CPLAT(150),CPLON(150),
     &EARLAT(150),EARLON(150),FESTIM(150),COST1(41,150),
     &COST2(150,26),ARCPGW(41,150),FUELOF(150),FARGWT(150),
     &PBLAT(150),PBLON(150),YY(150),XXDIF(91),BOMBON(150),
     &ENDDIS(150),ARDIST(150),EFFACT(91),DIFF(91),
     &EARGWT(150,26)
C
C     THIS DATA STATEMENT IS USED TO INITIALIZE ARCP AND EAR
C     LOCATIONS USING THE "AVERAGE" TANKER CONCEPT.
C
      DATA ARDIS,EARDIS/1800.,3160.,4060.,1930.,3245.,4120./
      PI=3.141592654
      RAD=180.0/PI
      REWIND 1
      REWIND 2
      REWIND 3
      REWIND 5
      REWIND 6
      REWIND 7
C
C     READ THE INPUT DATA FROM TAPES 1, 2, AND 3, AND CALCULATE THE
C     NUMBER OF BOMBER TRACKS, TOTAL NUMBER OF TANKERS AVAILABLE,
C     NUMBER OF TANKER BASES USED, AND THE TOTAL NUMBER OF POST
C     REFUELING BASES.
C
      I=1
   10 READ(1,*,END=20)BBLAT(I),BBLON(I),EPLAT(I),EPLON(I),EPFREQ(I)
      I=I+1
      GOTO 10
   20 NOTRKS=I-1
      I=1
      NOTAVL=0
   30 READ(2,*,END=40)TBLAT(I),TBLON(I),TKGWT(I),NOTKRS(I)
      NOTAVL=NOTAVL+NOTKRS(I)
      I=I+1
      GOTO 30
   40 NOTB=I-1
      I=1
   50 READ(3,*,END=60)PRBLAT(I),PRBLON(I),PRBCAP(I)
      I=I+1
      GOTO50
   60 NOPRB=I-1
      TAS=444.
      ITER=1
      BIGM=99999.
      NSUM=0
C
C     FOR EACH BOMBER TRACK, ASSIGN THE APPROPRIATE NUMBER OF
C     TANKERS FROM THOSE THAT ARE AVAILABLE.
C
```

```
      DO 80 I=1,NOTRKS
      CALL CIRCLE(BBLAT(I),BBLON(I),EPLAT(I),EPLON(I),X,Y)
      DIST(I)=X
      COURSE(I)=Y
      DLOTEP=DIST(I)-103.
      TLOTEP=(DLOTEP/TAS)*60.
      NOSEG=TLOTEP/30.
      TLEFT=TLOTEP-NOSEG*30.
      GWT=478.
      DO 70 J=1,NOSEG
      FF=10.27+.718*GWT
      IF(GWT.LE.340.)FF=40.73+.628*GWT
      FUEL=FF*.03
      GWT=GWT-FUEL
   70 CONTINUE
      FF=10.27+.718*GWT
      IF(GWT.LE.340.)FF=40.73+.628*GWT
      GWTEP=GWT-(FF*TLEFT*.001)
      UNREF(I)=GWTEP-218.3
      DIFF(I)=EPFREQ(I)-UNREF(I)
      NOTREQ(I)=1
      FUELS(I)=83.
      IF(DIFF(I).GT.83.)THEN
           NOTREQ(I)=2
           FUELS(I)=135.
      ENDIF
      IF(DIFF(I).GT.135.)THEN
           NOTREQ(I)=3
           FUELS(I)=164.
      ENDIF
      NSUM=NSUM+NOTREQ(I)
   80 CONTINUE
      NRID=0
      IF(NOTAVL.GE.NSUM)GOTO 130
      NRID=NSUM-NOTAVL
   90 DO 100 J=1,NOTRKS
      XDIF(J)=FUELS(J)-DIFF(J)
  100 CONTINUE
      FMAX=XDIF(1)
      DO 110 J=2,NOTRKS
      IF(XDIF(J).GT.FMAX)FMAX=XDIF(J)
  110 CONTINUE
      DO 120 I=1,NOTRKS
      IF(XDIF(I).EQ.FMAX)THEN
           NRID=NRID-1
           NOTREQ(I)=NOTREQ(I)-1
           IF(NOTREQ(I).EQ.2)THEN
                    FUELS(I)=135.
           ELSEIF(NOTREQ(I).EQ.1)THEN
                    FUELS(I)=83.
           ELSE
                    FUELS(I)=0.
           ENDIF
```

```
          GOTO 130
       ENDIF
  120  CONTINUE
  130  IF(NRID.GT.0)GOTO 90
C
C      DETERMINE INITIAL ARCP AND EAR LOCATIONS FOR EACH TRACK
C      USING THE "AVERAGE" TANKER DISTANCES.  ALSO DETERMINE THE
C      TIME REQUIRED FOR THE BOMBER TO GET TO THE ARCP.  THIS TIME
C      IS USED TO CHECK FOR TANKER FEASIBILITY AT EACH ARCP.
C
       NN=0
       DO 150 I=1,NOTRKS
       DO 140 J=1,NOTREQ(I)
       NN=NN+1
       CALL LATLON(BBLAT(I),BBLON(I),ARDIS(J),COURSE(I),S,T)
       CPLAT(NN)=S
       CPLON(NN)=T
       CALL LATLON(BBLAT(I),BBLON(I),EARDIS(J),COURSE(I),S,T)
       EARLAT(NN)=S
       EARLON(NN)=T
       FESTIM(NN)=((ARDIS(J)-164.)*60.)/TAS
  140  CONTINUE
  150  CONTINUE
       PRINT*,'******************************'
       PRINT*
       PRINT*,'            NETWORK'
       PRINT*
       PRINT*,'******************************'
  160  PRINT'(////)'
       PRINT*,'******************************'
       PRINT*,'      FOR ITERATION NUMBER    ',ITER
       PRINT*,'******************************'
       PRINT'(////)'
C
C      DETERMINE THE TOTAL NUMBER OF NODES IN THE NETWORK,
C      AND WRITE THIS AS THE FIRST ENTRY ON TAPE 5.
C
       M=NOTB+NOTAVL*2+NOPRB+1
       WRITE(5,280)M
C
C      DETERMINE ARC COSTS FROM EACH TANKER BASE TO EACH ARCP,
C      AND WRITE THIS ON TAPE 5 ALONG WITH THE UPPER AND LOWER
C      BOUNDS FOR EACH ARC.
C
       DO 200 I=1,NOTB
       DO 190 J=1,NN
       CALL CIRCLE(TBLAT(I),TBLON(I),CPLAT(J),CPLON(J),X,Y)
       DISTNC=X
       TIMER=((DISTNC-164.)*60.)/TAS
       NSEG=TIMER/30.
       TLEFT=TIMER-NSEG*30.
       GW=TKGWT(I)
       DO 170 K=1,NSEG
```

```
         FF=.856*GW+2.83
         IF(GW.LE.180.)FF=.813*GW+10.8
         FUEL=FF*.03
         GW=GW-FUEL
  170 CONTINUE
      FF=.856*GW+2.83
      IF(GW.LE.180.)FF=.813*GW+10.8
      GW=GW-((FF*TLEFT)*.001)
C
C     DETERMINE IF HOLDING IS REQUIRED
C
      FESTIM(J)=FESTIM(J)+.001
      IF(TIMER.GT.FESTIM(J))THEN
         COST1(I,J)=BIGM
      ELSE
         HTIME=FESTIM(J)-TIMER
         NSEG=HTIME/30.
         TLEFT=HTIME-NSEG*30.
         DO 180 K=1,NSEG
         FF=.9025*GW-18.89
         GW=GW-FF*.03
  180    CONTINUE
         FF=.9025*GW-18.89
         GW=GW-FF*TLEFT/1000.
         ARCPGW(I,J)=GW
         COST1(I,J)=110.1-GW
      ENDIF
      ICOST=COST1(I,J)*10000
      NODES=NOTB+J
      WRITE(5,270)I,NODES,ICOST,NOTKRS(I),0
  190 CONTINUE
  200 CONTINUE
C
C     WRITE REFUELING ARC DATA ONTO TAPE 5.
C
      ICOST=0
      DO 210 I=1,NN
      NODE=NODES+I
      J=NOTB+I
      WRITE(5,270)J,NODE,ICOST,1,1
  210 CONTINUE
C
C     DETERMINE ARC COSTS FROM EACH EAR NODE TO EACH PRB NODE.
C     THIS ARC COST INCLUDES A PROVISION FOR NOT CLIMBING TO
C     OPTIMUM ALTITUDE IF THE PRB IS NEARBY.  WRITE THE COSTS
C     AND UPPER AND LOWER BOUNDS ONTO TAPE 5.
C
      PRBGWT=115.1
      DO 240 I=1,NN
      DO 230 J=1,NOPRB
      CALL CIRCLE(EARLAT(I),EARLON(I),PRBLAT(J),PRBLON(J),X,Y)
      GW=PRBGWT
      IF(X.LE.140.)THEN
```

```
              TLEFT=X/TAS*60.
              GW=GW+.157*TLEFT
          ELSE
              DISTX=X-73.
              TIME=DISTX/TAS*60.
              NSEG=TIME/30.
              TLEFT=TIME-NSEG*30.
              DO 220 K=1,NSEG
                     GW=(GW+.3241)/.9756
  220         CONTINUE
              GW=GW+((.813*(GW+1.5)+10.8)*TLEFT/1000.)+2.
          ENDIF
          EARGWT(I,J)=GW
          COST2(I,J)=EARGWT(I,J)-PREGWT
          ICOST=COST2(I,J)*10000
          INODES=NODE+J
          II=NODES+I
          WRITE(5,270)II,INODES,ICOST,1,0
  230 CONTINUE
  240 CONTINUE
C
C     WRITE ONTO TAPE 5 THE ARC DATA FROM EACH OF THE PRBS
C     TO THE SECONDARY SINK NODE.
C
      ICOST=0
      DO 250 I=1,NOPRB
      JJ=NODE+I
      II=INODES+1
      WRITE(5,270)JJ,II,ICOST,PRBCAP(I),0
  250 CONTINUE
C
C     WRITE ONTO TAPE 5 THE ARC DATA FROM THE SECONDARY
C     SINK TO THE SUPER SINK.
C
      JJ=II+2
      WRITE(5,270)II,JJ,ICOST,NN,0
C
C     WRITE ONTO TAPE 5 THE ARC DATA FROM THE SOURCE
C     NODE TO EACH OF THE TANKER BASE NODES.
C
      DO 260 I=1,NOTB
      JJ=II+1
      WRITE(5,270)JJ,I,ICOST,NOTKRS(I),0
  260 CONTINUE
  270 FORMAT(6X,2I6,2X,3I10)
  280 FORMAT(I5)
  290 FORMAT(5X,2I5,5I10)
  300 FORMAT(6X,F12.0)
      REWIND 5
C
C     CALL THE GNET SUBROUTINE TO SOLVE FOR THE MINIMUM COST
C     FLOW THROUGH THE NETWORK THAT HAS BEEN DESCRIBED BY
C     TAPE 5.  THE ENTIRE GNET OUTPUT IS STORED ON TAPE 6,
C     AND THE ARC FLOWS ONLY ARE STORED ONTO TAPE 7.
```

```
      CALL GNETSS
      REWIND 9
      READ(9,300)RCOST
      PRINT*,' INITAL COST IS     ',RCOST
      PRINT'(///)'
      REWIND 7
C
C     READ TAPE 7 AND DETERMINE THE PRB MATINGS FROM
C     EACH OF THE EAR POINTS.  ALSO DETERMINE THE TANKER
C     GROSS WEIGHTS AT EACH OF THE EAR POINTS.
C
      NTIMES=NOTB*NOTAVL+NOTAVL
      DO 310 IA=1,NTIMES
      READ(7,290)IT,NH,IBL,IX,ICP,IC,IRC
  310 CONTINUE
      DO 330 IB=1,NOPRB
      DO 320 IS=1,NOTAVL
      IBB=NOTAVL+NOTB+IS
      IXC=2*NOTAVL+NOTB+IB
      READ(7,290)IT,NH,IBL,IX,ICP,IC,IRC
      IF(IX.GT.0.AND.IT.EQ.IBB.AND.NH.EQ.IXC)THEN
          FARGWT(IS)=EARGWT (IS,IB)
          PBLAT(IS)=PRBLAT(IB)
          PBLON(IS)=PRBLON(IB)
      ENDIF
  320 CONTINUE
  330 CONTINUE
      REWIND 7
C
C     READ TAPE 7 AGAIN TO DETERMINE THE TANKER TO BOMBER
C     ASSIGNMENTS.  ALSO DETERMINE THE FUEL CONSUMED ON
C     THE AR TRACK BY BOTH THE BOMBER AND TANKER.  DETERMINE
C     TANKER OFFLOAD CAPABILITY AND BOMBER ONLOAD CAPABILITY
C     FOR THE MATINGS GIVEN.
C
      DO 390 J=1,NM
      DO 380 I=1,NOTB
      READ(7,290)IT,NH,IBL,IX,ICP,IC,IRC
      JJ=NOTB+J
      IF(IX.GT.0.AND.I.EQ.IT.AND.JJ.EQ.NH)THEN
        CALL CIRCLE(CPLAT(J),CPLON(J),EARLAT(J),EARLON(J),X,Y)
        DISTNC=X
        TIME=DISTNC/400.*60.
        FF=.524*((ARCPGW(I,J)+FARGWT(J))/2)+67.71
        FUEL=FF*TIME/1000
        FUELOF(J)=ARCPGW(I,J)-FARGWT(J)-FUEL
        MM=0
        DO 370 K=1,NOTRKS
        DO 360 L=1,NOTREQ(K)
        MM=MM+1
        IF(J.EQ.MM)THEN
```

```
          CALL CIRCLE(BBLAT(K),BBLON(K),CPLAT(J),CPLON(J),X,Y)
          DISTY=X
          ARDIST(MM)=X
          TIMER=((DISTY-105.)/TAS)*60.
          NSEG=TIMER/30.
          TLEFT=TIMER-NSEG*30
          GW=478.
          DO 340 M=1,NSEG
          GW=GW-((10.27+.718*GW)*.03)
 340      CONTINUE
          BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
          IF(L.GT.1)THEN
               CALL CIRCLE(EARLAT(J-1),EARLON(J-1),CPLAT(J),
     &         CPLON(J),X,Y)
               DISST=X
               TIMES=DISST/TAS*60.
               NSEG=TIMES/30.
               TLEFT=TIMES-NSEG*30.
               GW=488.
               DO 350 IT=1,NSEG
               GW=GW-((10.27+.718*GW)*.03)
 350           CONTINUE
               BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
          ENDIF
          FUEL=TIME*(80.53+(BGWTCP+488.)/2*.7837)/1000.
          BOMBON(J)=488.-(BGWTCP-FUEL)
        ENDIF
 360    CONTINUE
 370    CONTINUE
      ENDIF
 380  CONTINUE
 390  CONTINUE
C
C     ARCPS AND EARS ARE NOW ADJUSTED A CERTAIN DISTANCE
C     IN AN ATTEMPT TO EQUATE BOMBER ONLOAD CAPABILITY WITH
C     TANKER OFFLOAD CAPABILITY.  THE DISTANCE THE ARCP IS
C     MOVED DEPENDS ON HOW MUCH THESE TWO NUMBERS DIFFER
C     INITIALLY.  NEW BOMBER TIMES TO THE ARCPS ARE ALSO
C     CALCULATED.
C
 400  J=0
      DO 420 I=1,NOTRKS
      DO 410 K=1,NOTREQ(I)
      J=J+1
      X=FUELOF(J)-BOMBON(J)
      IF(ABS(X).GT..4)THEN
          IF(X.GT.0)THEN
                 IF(X.LT..5)THEN
                 ARDIST(J)=ARDIST(J)+6.
                 ELSEIF(X.LT.1.)THEN
                 ARDIST(J)=ARDIST(J)+10.
                 ELSEIF(X.LT.2.)THEN
                 ARDIST(J)=ARDIST(J)+15.
```

```
              ELSEIF(X.LT.3.)THEN
              ARDIST(J)=ARDIST(J)+30.
              ELSEIF(X.LT.4.)THEN
              ARDIST(J)=ARDIST(J)+40.
              ELSEIF(X.LT.7.)THEN
              ARDIST(J)=ARDIST(J)+65.
              ELSEIF(X.LT.10.)THEN
              ARDIST(J)=ARDIST(J)+100.
              ELSEIF(X.LT.15.)THEN
              ARDIST(J)=ARDIST(J)+200.
              ELSEIF(X.LT.30.)THEN
              ARDIST(J)=ARDIST(J)+300.
              ELSEIF(X.GT.30.)THEN
              ARDIST(J)=ARDIST(J)+400.
              ENDIF
         ELSEIF(X.LT.0.)THEN
              IF(ABS(X).LT..5)THEN
              ARDIST(J)=ARDIST(J)-4.
              ELSEIF(ABS(X).LT.1.)THEN
              ARDIST(J)=ARDIST(J)-8.
              ELSEIF(ABS(X).LT.2.)THEN
              ARDIST(J)=ARDIST(J)-14.
              ELSEIF(ABS(X).LT.3.)THEN
              ARDIST(J)=ARDIST(J)-28.
              ELSEIF(ABS(X).LT.4.)THEN
              ARDIST(J)=ARDIST(J)-38.
              ELSEIF(ABS(X).LT.7.)THEN
              ARDIST(J)=ARDIST(J)-62.
              ELSEIF(ABS(X).LT.10.)THEN
              ARDIST(J)=ARDIST(J)-95.
              ELSEIF(ABS(X).LT.15.)THEN
              ARDIST(J)=ARDIST(J)-195.
              ELSEIF(ABS(X).LT.30.)THEN
              ARDIST(J)=ARDIST(J)-290.
              ELSEIF(ABS(X).GT.30.)THEN
              ARDIST(J)=ARDIST(J)-390.
              ENDIF
         ENDIF
      ENDIF
      ENDDIS(J)=ARDIST(J)+130.
      IF(K.GT.1)ENDDIS(J)=ARDIST(J)+95.
      IF(K.GT.2)ENDDIS(J)=ARDIST(J)+60.
      CALL LATLON(BBLAT(I),BBLON(I),ARDIST(J),COURSE(I),S,T)
      CPLAT(J)=S
      CPLON(J)=T
      CALL LATLON(BBLAT(I),BBLON(I),ENDDIS(J),COURSE(I),S,T)
      EARLAT(J)=S
      EARLON(J)=T
      FESTIM(J)=((ARDIST(J)-164.)*60.)/TAS
410   CONTINUE
420   CONTINUE
```

```
C     THE REMAINDER OF THE PROGRAM RECOMPUTES THE TANKER
C     OFFLOAD CAPABILITY AND BOMBER ONLOAD CAPABILITY AND
C     REITERATES THIS PROCEDURE UNTIL THE TWO NUMBERS ARE
C     WITHIN 400 POUNDS OF EACH OTHER.  BOMBER ENTRY POINT
C     FUEL IS COMPUTED FOR EACH BOMBER, AS WELL AS THE TOTAL
C     ENTRY POINT FUEL FOR THE BOMBER FLEET. ALSO, THE DIFFERENCES
C     BETWEEN BOMBER FUEL REQUIRED AND ACTUAL BOMBER FUEL IS
C     CALCULATED FOR EACH BOMBER.
C
      DO 440 J=1,NOTAVL
      CALL CIRCLE(PBLAT(J),PBLON(J),EARLAT(J),EARLON(J),X,Y)
      GW=PREGWT
      IF(X.LE.140.)THEN
          TLEFT=X/TAS*60.
          GW=GW+.157*TLEFT
      ELSE
          DISTX=X-73.
          TIME=DISTX/TAS*60.
          NSEG=TIME/30.
          TLEFT=TIME-NSEG*30.
          DO 430 KK=1,NSEG
                 GW=(GW+.3241)/.9756
  430     CONTINUE
          GW=GW+((.813*(GW+1.5)+10.8)*TLEFT/1000.)+2.
      ENDIF
      FARGWT(J)=GW
  440 CONTINUE
      REWIND 7
      DO 520 I=1,NOTAVL
      DO 510 J=1,NOTB
      READ(7,290)IT,NH,IBL,IX,ICP,IC,IRC
      JJ=NOTB+I
      IF(IX.GT.0.AND.J.EQ.IT.AND.JJ.EQ.NH)THEN
          CALL CIRCLE(TBLAT(J),TBLON(J),CPLAT(I),CPLON(I),S,T)
          DISTT=S
          TIMER=(DISTT-184.)*60./TAS
          NSEG=TIMER/30.
          TLEFT=TIMER-NSEG*30.
          GW=TKGWT(J)
          DO 450 L=1,NSEG
                 FF=.858*GW+2.83
                 IF(GW.LE.180.)FF=.813*GW+10.8
                 GW=GW-FF*.03
  450     CONTINUE
          FF=.858*GW+2.83
          IF(GW.LE.180.)FF=.813*GW+10.8
          GW=GW-FF*TLEFT/1000.
          HTIME=FESTIM(I)-TIMER
          NSEG=HTIME/30.
          TLEFT=HTIME-NSEG*30.
          DO 460 M=1,NSEG
                 FF=.9025*GW-16.88
                 GW=GW-FF*.03
  460     CONTINUE
```

```
      FF=.9025*GW-16.69
      GW=GW-FF*TLEFT/1000.
      ARCPGW(J,I)=GW
      CALL CIRCLE(CPLAT(I),CPLON(I),EARLAT(I),EARLON(I),X,Y)
      DISTT=X
      TIME=DISTT/400.*60.
      FF=.524*((ARCPGW(J,I)+FARGWT(I))/2)+67.71
      FUEL=FF*TIME/1000.
      FUELOF(I)=ARCPGW(J,I)-FARGWT(I)-FUEL
      MM=0
      DO 500 K=1,NOTRKS
      DO 490 L=1,NOTREQ(K)
      MM=MM+1
      IF(I.EQ.MM)THEN
             CALL CIRCLE(BBLAT(K),BBLON(K),CPLAT(I),CPLON(I),X,Y)
             DISTY=X
             TIMER=((DISTY-105.)/TAS)*60.
             NSEG=TIMER/30.
             TLEFT=TIMER-NSEG*30
             GW=478.
             DO 470 M=1,NSEG
             GW=GW-((10.27+.718*GW)*.03)
470          CONTINUE
             BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
             IF(L.GT.1)THEN
                CALL CIRCLE(EARLAT(I-1),EARLON(I-1),CPLAT(I),
   &            CPLON(I),X,Y)
                DISST=X
                TIMES=DISST/TAS*60.
                NSEG=TIMES/30.
                TLEFT=TIMES-NSEG*30.
                GW=488.
                DO 480 IT=1,NSEG
                GW=GW-((10.27+.718*GW)*.03)
480             CONTINUE
                BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
             ENDIF
             FUEL=TIME*(80.53+(BGWTCP+488.)/2.*.7837)/1000.
             BOMBON(I)=488.-(BGWTCP-FUEL)
      ENDIF
490   CONTINUE
500   CONTINUE
    ENDIF
510 CONTINUE
520 CONTINUE
    DO 530 I=1,NOTAVL
    YY(I)=ABS(FUELOF(I)-BOMBON(I))
530 CONTINUE
    YYY=YY(1)
    DO 540 J=2,NOTAVL
    IF(YY(J).GT.YYY)YYY=YY(J)
540 CONTINUE
    IF(YYY.GT..4)GOTO 400
```

```
      FSUM=0.
      J=0
      DO 560 I=1,NOTRKS
      J=J+NOTREQ(I)
      IF(NOTREQ(I).EQ.0)THEN
      EPFACT(I)=UNREF(I)
      ELSE
      CALL CIRCLE(EPLAT(I),EPLON(I),EARLAT(J),EARLON(J),X,Y)
      DISTT=X
      TIMER=DISTT/TAS*60.
      NSEG=TIMER/30.
      TLEFT=TIMER-NSEG*30.
      GW=488.
      DO 550 K=1,NSEG
           IF(GW.GT.340.)FF=10.27+.718*GW
           IF(GW.LE.340.)FF=40.73+.629*GW
           GW=GW-FF*.03
  550 CONTINUE
      IF(GW.GT.340.)FF=10.27+.718*GW
      IF(GW.LE.340.)FF=40.73+.629*GW
      GW=GW-FF*TLEFT/1000.
      EPFACT(I)=GW-218.3
      ENDIF
      FSUM=FSUM+EPFACT(I)
      XXDIF(I)=EPFACT(I)-EPFREQ(I)
  560 CONTINUE
      REWIND 5
      REWIND 6
      REWIND 7
      REWIND 8
      ITER=ITER+1
      IF(ITER.LE.10)GOTO 160
      STOP
      END
```

```
      PROGRAM GREEDY
C
C     THIS PROGRAM SOLVES THE TANKER TO BOMBER TO RECOVERY BASE
C     MATING PROBLEM USING A "GREEDY" TYPE ALGORITHM.  ASSIGNMENTS
C     ARE MADE BASED ON COST DIFFERENCES BETWEEN THE TWO BEST
C     POSSIBLE ASSIGNMENTS FOR A GIVEN REFUELING LOCATION, AND THE
C     REFUELING WITH THE BIGGEST DIFFERENCE IS ASSIGNED FIRST.
C     AFTER THE ASSIGNMENTS ARE MADE, INDIVIDUAL REFUELING LOCATIONS
C     ARE OPTIMIZED TO MAXIMIZE BOMBER ENTRY POINT FUEL. BOMBER,
C     TANKER, AND PRB DATA ARE THE INPUTS TO THE PROGRAM, AND THE
C     INDIVIDUAL ASSIGNMENTS AND REFUELING LOCATIONS ARE THE OUTPUTS.
C     ITERATIONS CAN BE MADE IN AN ATTEMPT TO IMPROVE THE ASSIGNMENT
C     PROCESS, AND INDIVIDUAL BOMBER ENTRY POINT FUELS CAN BE
C     OUTPUT AS WELL.
C
C
      COMMON/FACTOR/PI,RAD
C
C            FILE DEVICES USED IN THIS PROGRAM:
C
C     TAPE 1 ......................BOMBER INPUT DATA
C     TAPE 2 ......................TANKER INPUT DATA
C     TAPE 3 ......................RECOVERY BASE INPUT DATA
C     TAPE 7 ......................TANKER/BOMBER/PRB ASSIGNMENTS
C
C
C            INDEX OF IMPORTANT VARIABLES
C
C
C     NOTRKS..............NUMBER OF BOMBER TRACKS
C     NOTB................NUMBER OF TANKER BASES
C     NOPRB...............NUMBER OF POST REFUELING BASES
C     NOTAVL..............NUMBER OF TANKERS AVAILABLE
C
C
C     ARRAYS SHOULD BE DIMENSIONED AS FOLLOWS:
C
C     BBLAT,BBLON,EPLAT,EPLON,EPFREQ.........NOTRKS+1
C     TBLAT,TBLON,TKGWT,NOTKRS,NOTKS.........NOTB+1
C     PRBLAT,PRBLON,PRBCAP,PRBCP.............NOPRB+1
C     DIST,COURSE,DIFF,UNREF,FUELS,NOTREQ,
C     XDIF,EPFACT,XXDIF......................NOTRKS
C     CPLAT,CPLON,EARLAT,EARLON,FESTIM,
C     ARDIST,ENDDIS,FUELOF,BOMBON,YY,
C     BEST1,BEST2............................NOTAVL
C     COST1,ARCPGW...........................NOTB,NOTAVL
C     COST2,EARGWT...........................NOTAVL,NOPRB
C     COST3..................................NOTAVL,NOTB,NOPRB
C     ARDIS,EARDIS...........................3
```

```
      INTEGER NOTKRS(33),NOTREQ(91),PRBCAP(20)
     &,NOTKS(33),PRBCP(20)
      REAL BBLAT(91),BBLON(91),EPLAT(91),EPLON(91),EPFREQ(91),
     &TBLAT(33),TBLON(33),TKGWT(33),PRBLAT(20),PRBLON(20),
     &DIST(91),UNREF(91),FUELS(91),XDIF(91),ARDIS(3),
     &EARDIS(3),COURSE(91),CPLAT(135),CPLON(135),
     &EARLAT(135),EARLON(135),FESTIM(135),COST1(41,135),
     &COST2(135,20),ARCPGW(33,135),FUELOF(135),
     &YY(135),XXDIF(91),BOMBON(135),
     &ENDDIS(135),ARDIST(135),EFFACT(91),DIFF(135),
     &EARGWT(135,20),COST3(135,35,20),BEST1(135),BEST2(135)
C
C     THIS DATA STATEMENT IS USED TO INITIALIZE ARCP AND EAR
C     LOCATIONS USING THE "AVERAGE" TANKER CONCEPT.
C
      DATA ARDIS,EARDIS/1800.,3180.,4080.,1930.,3245.,4120./
      PI=3.141592654
      RAD=180.0/PI
      REWIND 1
      REWIND 2
      REWIND 3
      REWIND 7
C
C     READ THE INPUT DATA FROM TAPES 1, 2, AND 3, AND CALCULATE THE
C     NUMBER OF BOMBER TRACKS, TOTAL NUMBER OF TANKERS AVAILABLE,
C     NUMBER OF TANKER BASES USED, AND THE TOTAL NUMBER OF POST
C     REFUELING BASES.
C
      I=1
   10 READ(1,*,END=20)BBLAT(I),BBLON(I),EPLAT(I),EPLON(I),EPFREQ(I)
      I=I+1
      GOTO 10
   20 NOTRKS=I-1
      I=1
      NOTAVL=0
   30 READ(2,*,END=40)TBLAT(I),TBLON(I),TKGWT(I),NOTKRS(I)
      NOTAVL=NOTAVL+NOTKRS(I)
      I=I+1
      GOTO 30
   40 NOTB=I-1
      I=1
   50 READ(3,*,END=60)PRBLAT(I),PRBLON(I),PRBCAP(I)
      I=I+1
      GOTO50
   60 NOPRB=I-1
      TAS=444.
      ITER=1
      BIGM=99999.
      NSUM=0
C
C     FOR EACH BOMBER TRACK, ASSIGN THE APPROPRIATE NUMBER OF
C     TANKERS FROM THOSE THAT ARE AVAILABLE.
C
```

```
      DO 80 I=1,NOTRKS
      CALL CIRCLE(BBLAT(I),BBLON(I),EPLAT(I),EPLON(I),X,Y)
      DIST(I)=X
      COURSE(I)=Y
      DLOTEP=DIST(I)-105.
      TLOTEP=(DLOTEP/TAS)*60.
      NOSEG=TLOTEP/30.
      TLEFT=TLOTEP-NOSEG*30.
      GWT=470.
      DO 70 J=1,NOSEG
      FF=10.27+.718*GWT
      IF(GWT.LE.340.)FF=40.73+.629*GWT
      FUEL=FF*.03
      GWT=GWT-FUEL
   70 CONTINUE
      FF=10.27+.718*GWT
      IF(GWT.LE.340.)FF=40.73+.629*GWT
      GWTEP=GWT-(FF*TLEFT*.001)
      UNREF(I)=GWTEP-218.3
      DIFF(I)=EPFREQ(I)-UNREF(I)
      NOTREQ(I)=1
      FUELS(I)=83.
      IF(DIFF(I).GT.83.)THEN
           NOTREQ(I)=2
           FUELS(I)=135.
      ENDIF
      IF(DIFF(I).GT.135.)THEN
           NOTREQ(I)=3
           FUELS(I)=164.
      ENDIF
      NSUM=NSUM+NOTREQ(I)
   80 CONTINUE
      NRID=0
      IF(NOTAVL.GE.NSUM)GOTO 130
      NRID=NSUM-NOTAVL
   90 DO 100 J=1,NOTRKS
      XDIF(J)=FUELS(J)-DIFF(J)
  100 CONTINUE
      FMAX=XDIF(1)
      DO 110 J=2,NOTRKS
      IF(XDIF(J).GT.FMAX)FMAX=XDIF(J)
  110 CONTINUE
      DO 120 I=1,NOTRKS
      IF(XDIF(I).EQ.FMAX)THEN
           NRID=NRID-1
           NOTREQ(I)=NOTREQ(I)-1
           IF(NOTREQ(I).EQ.2)THEN
                   FUELS(I)=135.
           ELSEIF(NOTREQ(I).EQ.1)THEN
                   FUELS(I)=83.
           ELSE
                   FUELS(I)=0.
           ENDIF
```

```
          GOTO 130
        ENDIF
  120 CONTINUE
  130 IF(NRID.GT.0)GOTO 90
C
C       DETERMINE INITIAL ARCP AND EAR LOCATIONS FOR EACH TRACK
C       USING THE "AVERAGE" TANKER DISTANCES.  ALSO DETERMINE THE
C       TIME REQUIRED FOR THE BOMBER TO GET TO THE ARCP.  THIS TIME
C       IS USED TO CHECK FOR TANKER FEASIBILITY AT EACH ARCP.
C
      NN=0
      DO 150 I=1,NOTRKS
      DO 140 J=1,NOTREQ(I)
      NN=NN+1
      CALL LATLON(BBLAT(I),BBLON(I),ARDIS(J),COURSE(I),S,T)
      CPLAT(NN)=S
      CPLON(NN)=T
      CALL LATLON(BBLAT(I),BBLON(I),EARDIS(J),COURSE(I),S,T)
      EARLAT(NN)=S
      EARLON(NN)=T
      FESTIM(NN)=((ARDIS(J)-164.)*60.)/TAS
  140 CONTINUE
  150 CONTINUE
      PRINT*,'*******************************'
      PRINT*
      PRINT*,'            GREEDY'
      PRINT*
      PRINT*,'*******************************'
  160 PRINT'(////)'
      PRINT*,'*******************************'
      PRINT*,'      FOR ITERATION NUMBER     ',ITER
      PRINT*,'*******************************'
      DO 161 I=1,NOPRB
      PRBCP(I)=PRBCAP(I)
  161 CONTINUE
      DO 162 I=1,NOTB
      NOTKS(I)=NOTKRS(I)
  162 CONTINUE
C
C DETERMINE COSTS FROM EACH TANKER BASE TO EACH ARCP
C
      DO 200 I=1,NOTB
      DO 190 J=1,NOTAVL
      CALL CIRCLE(TBLAT(I),TBLON(I),CPLAT(J),CPLON(J),X,Y)
      DISTNC=X
      TIMER=((DISTNC-164.)*60.)/TAS
      NSEG=TIMER/30.
      TLEFT=TIMER-NSEG*30.
      GW=TKGWT(I)
      DO 170 K=1,NSEG
          FF=.050*GW+2.83
          IF(GW.LE.180.)FF=.013*GW+10.0
          FUEL=FF*.83
          GW=GW-FUEL
```

```
  170 CONTINUE
      FF=.858*GW+2.83
      IF(GW.LE.180.)FF=.813*GW+10.8
      GW=GW-((FF*TLEFT)*.001)
C
C
C     DETERMINE IF HOLDING IS REQUIRED
C
C
      FESTIM(J)=FESTIM(J)+.001
      IF(TIMER.GT.FESTIM(J))THEN
          COST1(I,J)=BIGM
      ELSE
          HTIME=FESTIM(J)-TIMER
          NSEG=HTIME/30.
          TLEFT=HTIME-NSEG*30.
          DO 180 K=1,NSEG
          FF=.9025*GW-16.88
          GW=GW-FF*.03
  180     CONTINUE
          FF=.9025*GW-16.88
          GW=GW-FF*TLEFT/1000.
          ARCPGW(I,J)=GW
          COST1(I,J)=110.1-GW
      ENDIF
  190 CONTINUE
  200 CONTINUE
C
C
C     DETERMINE COSTS FROM EACH EAR POINT TO EACH PRB
C     THIS COST INCLUDES A PROVISION FOR NOT CLIMBING
C     TO OPTIMUM ALTITUDE IF THE PRB IS NEARBY
C
C
      PRBGWT=115.1
      DO 240 I=1,NOTAVL
      DO 230 J=1,NOPRB
      CALL CIRCLE(EARLAT(I),EARLON(I),PRBLAT(J),PRBLON(J),X,Y)
      GW=PRBGWT
      IF(X.LE.140.)THEN
          TLEFT=X/TAS*60.
          GW=GW+.157*TLEFT
      ELSE
          DISTX=X-73.
          TIME=DISTX/TAS*60.
          NSEG=TIME/30.
          TLEFT=TIME-NSEG*30.
          DO 220 KK=1,NSEG
                 GW=(GW+.3241)/.0756
  220     CONTINUE
          GW=GW+((.813*(GW+1.5)+10.8)*TLEFT/1000.)+2.
      ENDIF
      EARGWT(I,J)=GW
      COST2(I,J)=EARGWT(I,J)-PRBGWT
```

```
  230 CONTINUE
  240 CONTINUE
C
C
C     DETERMINE TOTAL COST FOR EACH TANKER BASE,
C     REFUELING LOCATION, PRB COMBINATION.  THIS
C     IS DONE BY ADDING TOGETHER THE TWO COSTS
C     PREVIOUSLY CALCULATED.
C
C
      DO 260 I=1,NOTAVL
      DO 250 J=1,NOTB
      DO 245 K=1,NOPRB
      COST3(I,J,K)=COST1(J,I)+COST2(I,K)
      IF(COST3(I,J,K).GT.BIGM)COST3(I,J,K)=BIGM
  245 CONTINUE
  250 CONTINUE
  260 CONTINUE
      NN=NOTAVL
C
C
C     FIND THE TWO BEST COSTS FOR EACH REFUELING,
C     AND FROM THESE FIND THE REFUELING WITH THE
C     LARGEST DIFFERENCE AND BEST COST.  THIS
C     REFUELING WILL BE ASSIGNED FIRST.  WRITE
C     THE REFUELING ASSIGNMENTS ONTO TAPE 7.
C
C
  270 BIGDIF=0.
      DO 300 I=1,NOTAVL
      BEST1(I)=BIGM
      BEST2(I)=BIGM
      DO 290 J=1,NOTB
      DO 280 K=1,NOPRB
      IF(COST3(I,J,K).LE.BEST1(I))THEN
          BEST1(I)=COST3(I,J,K)
          KFACE=J
      ENDIF
  280 CONTINUE
  290 CONTINUE
      DO 291 J=1,NOTB
      DO 292 K=1,NOPRB
      IF(COST3(I,J,K).GE.BEST1(I).AND.COST3(I,J,K).LE.BEST2(I).AND.
     &KFACE.NE.J)BEST2(I)=COST3(I,J,K)
  292 CONTINUE
  291 CONTINUE
      DIFF(I)=BEST2(I)-BEST1(I)
      IF(DIFF(I).GT.BIGDIF)THEN
          BIGDIF=DIFF(I)
          IFACE=I
      ENDIF
  300 CONTINUE
      DO 380 J=1,NOTB
```

```
      DO 350 K=1,NOPRB
      IF(COST3(IFACE,J,K).EQ.BEST1(IFACE))THEN
          PRBCP(K)=PRBCP(K)-1
          NOTKS(J)=NOTKS(J)-1
          IF(PRBCP(K).EQ.0)THEN
                 DO 320 II=1,NOTAVL
                 DO 310 JJ=1,NOTB
                 COST3(II,JJ,K)=BIGM
 310             CONTINUE
 320             CONTINUE
          ENDIF
          IF(NOTKS(J).EQ.0)THEN
                 DO 340 II=1,NOTAVL
                 DO 330 KK=1,NOPRB
                 COST3(II,J,KK)=BIGM
 330             CONTINUE
 340             CONTINUE
          ENDIF
          WRITE(7,*)J,IFACE,K
          GOTO 385
      ENDIF
 350  CONTINUE
 380  CONTINUE
 385  DO 366 J=1,NOTB
      DO 367 K=1,NOPRB
      COST3(IFACE,J,K)=BIGM
 367  CONTINUE
 366  CONTINUE
      NN=NN-1
      IF(NN.GT.0)GOTO 270
      REWIND 7
      M=0
      DO 410 I=1,NOTRKS
      DO 400 J=1,NOTREQ(I)
      M=M+1
      DO 390 K=1,NOTAVL
      READ(7,*)ITB,IAR,IPRB
      IF(IAR.EQ.M)THEN
C
C     COMPUTE TANKER OFFLOAD CAPABILITY
C
         CALL CIRCLE(CPLAT(M),CPLON(M),EARLAT(M),EARLON(M),X,Y)
         DISTNC=X
         TIME=(DISTNC/400.)*60.
         FF=.524*((ARCPGW(ITB,IAR)+EARGWT(IAR,IPRB))/2.)+87.71
         FUEL=TIME*FF*.001
         FUELOF(M)=ARCPGW(ITB,IAR)-EARGWT(IAR,IPRB)-FUEL
C
C     COMPUTE BOMBER ONLOAD CAPABILITY
C
         CALL CIRCLE(BBLAT(I),BBLON(I),CPLAT(M),CPLON(M),X,Y)
         ARDIST(M)=X
```

```
         IF(J.EQ.1)THEN
         TIMER=((ARDIST(M)-105.)/TAS)*60.
         NSEG=TIMER/30.
         TLEFT=TIMER-NSEG*30.
         GW=478.
         DO 370 L=1,NSEG
         GW=GW-((10.27+.718*GW)*.03)
 370     CONTINUE
         BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
      ELSE
         CALL CIRCLE(EARLAT(M-1),EARLON(M-1),CPLAT(M),CPLON(M),X,Y)
         DISST=X
         TIMES=DISST/TAS*60.
         NSEG=TIMES/30.
         TLEFT=TIMES-NSEG*30.
         GW=488.
         DO 380 L=1,NSEG
         GW=GW-((10.27+.718*GW)*.03)
 380     CONTINUE
         BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
         ENDIF
         FUEL=(80.53+(BGWTCP+488.)/2.*.7837)/1000.*TIME
         BOMBON(M)=488.-BGWTCP+FUEL
         REWIND 7
         GO TO 400
      ENDIF
 390  CONTINUE
 400  CONTINUE
 410  CONTINUE
C
C
C     ARCPS AND EARS ARE NOW ADJUSTED A CERTAIN DISTANCE
C     IN AN ATTEMPT TO EQUATE BOMBER ONLOAD CAPABILITY WITH
C     WITH TANKER OFFLOAD CAPABILITY.  THE DISTANCE THE ARCP
C     IS MOVED DEPENDS ON HOW MUCH THESE TWO NUMBERS DIFFER
C     INITIALLY.  NEW BOMBER TIMES TO THE ARCPS ARE ALSO
C     CALCULATED.
C
C
 401  J=0
      DO 420 I=1,NOTRKS
      DO 415 K=1,NOTREQ(I)
      J=J+1
      X=FUELOF(J)-BOMBON(J)
      IF(ABS(X).GT..4)THEN
          IF(X.GT.0)THEN
                 IF(X.LT..5)THEN
                 ARDIST(J)=ARDIST(J)+6.
                 ELSEIF(X.LT.1.)THEN
                 ARDIST(J)=ARDIST(J)+10.
                 ELSEIF(X.LT.2.)THEN
                 ARDIST(J)=ARDIST(J)+15.
```

```
                 ELSEIF(X.LT.3.)THEN
                 ARDIST(J)=ARDIST(J)+30.
                 ELSEIF(X.LT.4.)THEN
                 ARDIST(J)=ARDIST(J)+40.
                 ELSEIF(X.LT.7.)THEN
                 ARDIST(J)=ARDIST(J)+65.
                 ELSEIF(X.LT.10.)THEN
                 ARDIST(J)=ARDIST(J)+100.
                 ELSEIF(X.LT.15.)THEN
                 ARDIST(J)=ARDIST(J)+200.
                 ELSEIF(X.LT.30.)THEN
                 ARDIST(J)=ARDIST(J)+300.
                 ELSEIF(X.GT.30.)THEN
                 ARDIST(J)=ARDIST(J)+400.
                 ENDIF
          ELSEIF(X.LT.0.)THEN
                 IF(ABS(X).LT..5)THEN
                 ARDIST(J)=ARDIST(J)-4.
                 ELSEIF(ABS(X).LT.1.)THEN
                 ARDIST(J)=ARDIST(J)-8.
                 ELSEIF(ABS(X).LT.2.)THEN
                 ARDIST(J)=ARDIST(J)-14.
                 ELSEIF(ABS(X).LT.3.)THEN
                 ARDIST(J)=ARDIST(J)-28.
                 ELSEIF(ABS(X).LT.4.)THEN
                 ARDIST(J)=ARDIST(J)-38.
                 ELSEIF(ABS(X).LT.7.)THEN
                 ARDIST(J)=ARDIST(J)-62.
                 ELSEIF(ABS(X).LT.10.)THEN
                 ARDIST(J)=ARDIST(J)-85.
                 ELSEIF(ABS(X).LT.15.)THEN
                 ARDIST(J)=ARDIST(J)-195.
                 ELSEIF(ABS(X).LT.30.)THEN
                 ARDIST(J)=ARDIST(J)-290.
                 ELSEIF(ABS(X).GT.30.)THEN
                 ARDIST(J)=ARDIST(J)-390.
                 ENDIF
          ENDIF
      ENDIF
      ENDDIS(J)=ARDIST(J)+130.
      IF(K.GT.1)ENDDIS(J)=ARDIST(J)+85.
      IF(K.GT.2)ENDDIS(J)=ARDIST(J)+60.
      CALL LATLON(BBLAT(I),BBLON(I),ARDIST(J),COURSE(I),S,T)
      CPLAT(J)=S
      CPLON(J)=T
      CALL LATLON(BBLAT(I),BBLON(I),ENDDIS(J),COURSE(I),S,T)
      EARLAT(J)=S
      EARLON(J)=T
      FESTIM(J)=((ARDIST(J)-184.)*60.)/TAS
  415 CONTINUE
  420 CONTINUE
```

```
C     THE REMAINDER OF THE PROGRAM RECOMPUTES THE TANKER
C     OFFLOAD CAPABILITY AND BOMBER ONLOAD CAPABILITY AND
C     REITERATES THIS PROCEDURE UNTIL THE TWO NUMBERS ARE
C     WITHIN 400 POUNDS OF EACH OTHER.  BOMBER ENTRY POINT
C     FUEL IS COMPUTED FOR EACH BOMBER, AS WELL AS THE TOTAL
C     ENTRY POINT FUEL FOR THE BOMBER FLEET.  ALSO, THE
C     DIFFERENCES BETWEEN BOMBER FUEL REQUIRED AND ACTUAL
C     BOMBER FUEL IS CALCULATED FOR EACH BOMBER.
C
C
      REWIND 7
C
      M=0
      DO 910 I=1,NOTRKS
      DO 920 J=1,NOTREQ(I)
      M=M+1
      DO 930 K=1,NOTAVL
      READ(7,*)ITB,IAR,IPRB
      IF(IAR.EQ.M)THEN
C
C     COMPUTE TANKER OFFLOAD CAPABILITY
C
          CALL CIRCLE(TBLAT(ITB),TBLON(ITB),CPLAT(M),CPLON(M),X,Y)
          DISTNC=X
          TIMER=((DISTNC-164.)*60.)/TAS
          NSEG=TIMER/30.
          TLEFT=TIMER-NSEG*30.
          GW=TKGWT(ITB)
          DO 700 L=1,NSEG
                 FF=.858*GW+2.83
                 IF(GW.LE.180.)FF=.813*GW+10.8
                 FUEL=FF*.03
                 GW=GW-FUEL
  700            CONTINUE
          FF=.858*GW+2.83
          IF(GW.LE.180.)FF=.813*GW+10.8
          GW=GW-((FF*TLEFT)*.001)
C
C     DETERMINE IF HOLDING IS REQUIRED
C
          HTIME=FESTIM(M)-TIMER+.001
          NSEG=HTIME/30.
          TLEFT=HTIME-NSEG*30.
          DO 710 LL=1,NSEG
                 FF=.9025*GW-18.89
                 GW=GW-FF*.03
  710            CONTINUE
          FF=.9025*GW-18.89
          GW=GW-FF*TLEFT/1000.
          ARCPGW(ITB,M)=GW
```

```
C     COMPUTE NEW EARGWT FOR ASSIGNED PRB AND NEW EAR
C
          CALL CIRCLE(EARLAT(M),EARLON(M),PRBLAT(IPRB),
     &    PRBLON(IPRB),X,Y)
          GW=PRBGWT
      IF(X.LE.140.)THEN
          TLEFT=X/TAS*60.
          GW=GW+.157*TLEFT
      ELSE
          DISTX=X-73.
          TIME=DISTX/TAS*60.
          NSEG=TIME/30.
          TLEFT=TIME-NSEG*30.
          DO 720 KK=1,NSEG
                 GW=(GW+.3241)/.9756
 720      CONTINUE
          GW=GW+((.613*(GW+1.5)+10.6)*TLEFT/1000.)+2.
      ENDIF
          EARGWT(M,IPRB)=GW
C
C
        CALL CIRCLE(CPLAT(M),CPLON(M),EARLAT(M),EARLON(M),X,Y)
        DISTNC=X
        TIME=(DISTNC/400.)*60.
        FF=.524*((ARCPGW(ITB,IAR)+EARGWT(IAR,IPRB))/2.)+67.71
        FUEL=TIME*FF*.001
        FUELOF(M)=ARCPGW(ITB,IAR)-EARGWT(IAR,IPR3)-FUEL
C
C     COMPUTE BOMBER ONLOAD CAPABILITY
C
        CALL CIRCLE(BBLAT(I),BBLON(I),CPLAT(M),CPLON(M),X,Y)
        ARDIST(M)=X
         IF(J.EQ.1)THEN
        TIMER=((ARDIST(M)-105.)/TAS)*60.
        NSEG=TIMER/30.
        TLEFT=TIMER-NSEG*30.
        GW=476.
        DO 940 L=1,NSEG
        GW=GW-((10.27+.718*GW)*.03)
 940    CONTINUE
        BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
         ELSE
           CALL CIRCLE(EARLAT(M-1),EARLON(M-1),CPLAT(M),CPLON(M),X,Y)
           DISST=X
           TIMES=DISST/TAS*60.
           NSEG=TIMES/30.
         TLEFT=TIMES-NSEG*30.
           GW=488.
           DO 950 L=1,NSEG
           GW=GW-((10.27+.718*GW)*.03)
 950       CONTINUE
           BGWTCP=GW-((10.27+.718*GW)*TLEFT/1000.)
        ENDIF
```

```
         FUEL=(90.53+(BGWTCP+488.)/2.*.7837)/1000.*TIME
         BOMBON(M)=488.-BGWTCP+FUEL
         REWIND 7
         GO TO 920
      ENDIF
  930 CONTINUE
  920 CONTINUE
  910 CONTINUE
C
C
C
      DO 530 I=1,NOTAVL
      YY(I)=ABS(FUELOF(I)-BOMBON(I))
  530 CONTINUE
      YYY=YY(1)
      DO 540 J=2,NOTAVL
      IF(YY(J).GT.YYY)YYY=YY(J)
  540 CONTINUE
      IF(YYY.GT..4)GOTO 401
      FSUM=0.
      J=0
      DO 560 I=1,NOTRKS
      J=J+NOTREQ(I)
      IF(NOTREQ(I).EQ.0)THEN
      EPFACT(I)=UNREF(I)
      ELSE
      CALL CIRCLE(EPLAT(I),EPLON(I),EARLAT(J),EARLON(J),X,Y)
      DISTT=X
      TIMER=DISTT/TAS*60.
      NSEG=TIMER/30.
      TLEFT=TIMER-NSEG*30.
      GW=488.
      DO 550 K=1,NSEG
          IF(GW.GT.340.)FF=10.27+.718*GW
          IF(GW.LE.340.)FF=40.73+.629*GW
          GW=GW-FF*.03
  550 CONTINUE
      IF(GW.GT.340.)FF=10.27+.718*GW
      IF(GW.LE.340.)FF=40.73+.629*GW
      GW=GW-FF*TLEFT/1000.
      EPFACT(I)=GW-218.3
      ENDIF
      FSUM=FSUM+EPFACT(I)
      XXDIF(I)=EPFACT(I)-EPFREQ(I)
  560 CONTINUE
      ITER=ITER+1
      IF(ITER.LE.5)GOTO 160
      END
```

```
      SUBROUTINE CIRCLE(LAT,LONG,XLAT,XLONG,DIST,COURSE)
C     THIS SUBROUTINE COMPUTES THE GREAT CIRCLE COURSE AND DISTANCE
C     BETWEEN TWO POINTS
      COMMON/FACTOR/PI,RAD
      REAL LAT,LONG,DIST,COURSE,XLAT,XLONG
      P1=LAT/RAD
      P1M=LONG/RAD
      P2=XLAT/RAD
      P2M=XLONG/RAD
      QD=1.570796327
      IF(P1.GT.QD) P1=QD
      IF(P2.GT.QD) P2=QD
      D=ACOS(SIN(P1)*SIN(P2)+COS(P1)*COS(P2)*COS(P2M-P1M))
      RHO=D*3437.74677
      THETA=ACOS((SIN(P2)-SIN(P1)*COS(D))/SIN(D)/COS(P1))
      IF(SIN(P2M-P1M).GE.0) THETA=2*PI-THETA
      DIST=RHO
      COURSE=THETA*RAD
      RETURN
      END
C
C
      SUBROUTINE LATLON(LAT,LONG,DIST,COURSE,XLAT,XLONG)
C
C     THIS SUBROUTINE COMPUTES A NEW LATITUDE AND LONGITUDE GIVEN
C     AN INITIAL LATITUDE AND LONGITUDE AND A DISTANCE AND COURSE.
C
      COMMON/FACTOR/PI,RAD
      REAL LAT,LONG,DIST,COURSE,XLAT,XLONG
      RHO=DIST
      P1=LAT/RAD
      P1M=LONG/RAD
      THETA=COURSE/RAD
      R=RHO/3437.74677
      P2=ASIN(SIN(P1)*COS(R)+COS(P1)*SIN(R)*COS(THETA))
      XXX=(COS(R)-SIN(P1)*SIN(P2))/COS(P1)/COS(P2)
      D=ACOS(XXX)
      IF(SIN(THETA).GE.0.0) D=-D
      P2M=P1M+D
      IF(P2M.GE.0.0.AND.SIN(P2M).LT.0.0) P2M=P2M-2*PI
      IF(P2M.LT.0.0.AND.SIN(P2M).GT.0.0) P2M=P2M+2*PI
      XLAT=P2*RAD
      XLONG=P2M*RAD
      RETURN
      END
```

Appendix D

GNET Characteristics

Introduction

This appendix describes some of the characteristics of the GNET subroutine. It contains excerpts from References 2 and 7. The actual subroutine is not included in this report because it is proprietary information. The reader is directed to Reference 2 for information on how to obtain the actual program listing.

The Code and Its Capabilities

GNET is a machine independent FORTRAN program for the solution of the capacitated transshipment problem. The capacitated transshipment problem is the most general of the minimum cost flow models which include the capacitated and uncapacitated transportation problems and the personnel assignment problems.

The capacitated transshipment model and its specializations are minimum cost network flow problems. The goal is to determine how (or at what rate) a good should flow through the arcs of a network to minimize shipment costs. The transportation and assignment models are simplifications of this transshipment formulation.

Unlike the usual textbook approach, data is stored only for the arcs that are present in the network. This saves storage and computations since for most practical problems every node is not connected to every other node.

It is also permissible to use multiple arcs to model piecewise linear convex shipping costs.

GNET performs a primal network simplex algorithm by structural manipulation of a list structure representation of the network minimization problem and its triangulated bases. Each basis of the network problem is stored as a rooted arborescence and the pivotal transformations are performed structurally rather than by numerical matrix operations. GNET has been designed with selective safeguards that guarantee successful optimization from both programming and mathematical viewpoints. The code exhibits the following general features:

A. Exact Solutions. The solutions produced are absolutely free of rounding error. (Data and all calculations are integer.)

B. Problem Size. The code has been calibrated, tuned, and tested on problems with nominal sizes of 10^4 nodes and 10^5 arcs. Modified versions have successfully solved problems an order of magnitude larger.

C. Machine Independence. The routine is written in FORTRAN V and has been tested and tuned on most major computer systems including AMDAHL, Burroughs, CDC, Honeywell, IBM, UNIVAC, and TI/ASC. The user must specify the largest representable absolute integer ("BIGI") and make adjustments only for any nonstandard FORTRAN restrictions.

D. Storage Economy. The algorithm uses much less memory for execution than any known competing method. Using IBM "words" as a unit, the net region requirement for (standard version) GNET and data arrays is 1,600 + 9M + 3N where M is the number of nodes, and N is the number of arcs.

E. Non-Cycling Algorithm. The algorithm cannot cycle in the presence of primal degeneracy. A terminal solution is guaranteed.

F. Robustness. GNET has been tuned on hundreds of diverse problem formulations. The candidate queue pricing mechanism provides an extremely powerful problem-adaptive control for pivot trajectories which automatically exploits special problem structure. The pricing parameters for the candidate queue are automatically set at default values for excellent general performance. However, significant further improvements in efficiency are possible by custom adjustment of the parameters for classes of problems exhibiting very unorthodox structure.

G. Adaptability. GNET can solve network problems of extremely large size without further modification. Moreover, the candidate queue mechanism is designed to permit modification for truly huge problems.

Subroutine NTRD Input Example

GNET uses an input subroutine called NTRD. The subroutine reads in the input data from a file using the following format and structure:

1. Header card (I5) number of nodes in the network, M.

2. Arc description cards:

column	format	item
1-4	A4	"Name" of arc (optional)
5-6	2X	(Not used)
7-12	I6	Source of node of arc
13-18	I6	Destination node of arc
19-20	2X	(Not used)
21-30	I10	Cost per unit flow
31-40	I10	Capacity of arc
41-50	I10	Lower bound of arc

3. End of file.

Supplies and demands can be input by using "dummy" arcs (not explicitly stored after input). NTRD will assume two "artificial nodes" numbered M+1 and M+2. Node M+1 is a "super source" to the problem, and node M+2 is a "super sink." Supplies to the network are specified as "dummy" arc capacities from node M+1 to the source nodes involved. Demands are given as "dummy" arc capacities from the destination, or sink nodes, to node M+2.

All costs must be integers. Use of decimal points on input is not allowed. Also, all integers must be "right-oriented" in the appropriate fields. Zero costs are admissible.

All arcs must have capacities that are nonnegative integers. To create an "uncapacitated" arc, give the arc a positive capacity just greater than the total of all supplies to the problem.

Nodes should be numbered 1,2,...,M with positive integers. It is not necessary to use all the numbers between 1 and M. Numbering is arbitrary with respect to arc orientation. Any sequence of arc description records is acceptable. Multiple arcs between any two nodes are admissible.

GNET solves the all-equation transshipment problem, thus total supply must equal total demand. Inequality problems are easily transformed to this form by the addition of an extra node and "slack" arcs. The input is described here for the usual case of zero lower bounds, positive capacities and no arcs with fixed flow.

Sample Problem Input

```
CARD                 1         2         3         4         5
COLUMNS:    12345678901234567890123456789012345678901234567890

header:           7
arcs:       AB        1    3         3     100        0
            AC        1    4         6     100        0
            AG        1    2         0      50        0
            BC        3    4         1     200        0
            BD        3    7         1     300        0
            CD        4    7         2     100        0
            CF        4    5         6     150        0
            D-        7    9         0     120        0
            ED        6    7        11     200        0
            E-        6    9         0      70        0
            FC        5    4         5     150        0
            FE        5    6         8      90        0
            FE        5    6         5      50        0
            GC        2    4         4      50        0
            GF        2    5         2     400        0
            -A        8    1         0      90        0
            -G        8    2         0     100        0

end:        *eor
```

Problem Feasibility and the Scaling of Arc Costs

For some minimum cost flow models, such as the classic assignment problem, there is always a feasible solution and thus an optimal solution. In general, however, even if total supply equals total demand, there may not be a feasible solution.

GNET introduces artificial arcs into the initial basis and then drives their flows to zero for a feasible solution. At termination, if the flow on all artificial arcs is zero, the final solution is feasible, and thus optimal. If any artificial arc has positive flow, the problem has no feasible solution.

For the artificial arcs, GNET calculates a large positive cost, BIGM, which guarantees that the flows on these arcs will be zero for a feasible solution. However, the size of the problem, the scale of the costs, and the value of the largest integer representable on the machine may limit BIGM to something less than this calculated value. If BIGM is limited in this way a warning is printed, and a cost scaling flag, ISCALE, is set equal to 1. In this case, GNET will still terminate normally: if the final solution is feasible, it is also optimal; if the final solution is not feasible, it is possible (although this is highly unlikely because the criterion is so conservative) that the problem actually does have an undiscovered feasible solution. Rescaling the costs to a smaller range will avoid this potential problem.

Vitae

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William Leslie MacElhaney was born on 30 October 1951 in Baltimore, Maryland. He graduated from high school in Colorado Springs, Colorado in 1969 and attended the United States Air Force Academy graduating in June 1974 with a Bachelor of Science degree in Mechanical Engineering. He attended Undergraduate Navigator Training and received his wings in March 1975. He then served as a KC-135 navigator and flight instructor with the 909th Air Refueling Squadron, Kadena AB, Okinawa, Japan until 1977. He was then assigned as a squadron navigator, instructor navigator, and standardization and evaluation navigator with the 905th Air Refueling Squadron and 319th Bomb Wing, Grand Forks AFB, North Dakota. He entered the School of Engineering, Air Force Institute of Technology in August 1980. He is married to the former YuChuan Wang, and they have two sons, David Neal and Kevin Leslie.

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The survivability of the strategic bomber force during Emergency War Order missions is of primary concern to the Strategic Air Command. Since the Soviet Union and its Warsaw Pact allies possess the most extensive air defense networks in the world, a penetrating bomber force must fly as low as possible for as long as possible. This tactic minimizes probability of detection and vulnerability to defensive threats. It also greatly increases the fuel required to complete the mission. This additional fuel is supplied by one or more in-flight refuelings.

The initial objective of this thesis was to develop a method for assigning tankers to the bomber force in an optimal manner. As the study progressed however, it became clear that obtaining a truly optimal solution using mathematical programming techniques cannot be guaranteed due to the nature and complexity of the problem. As a result the emphasis of the study was shifted to developing an improved method for solving the problem.

Two heuristic methods were investigated. The first method used network theory in an attempt to minimize the costs of assigning tankers to the bombers. The second method was based on the so-called "greedy" method. This method basically made the assignments in the order of decreasing marginal cost improvements. These two methods were evaluated against each other and the current method by means of several example problems. Both methods yielded better results than the one currently in use, with the network method appearing to be the best.

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